NASA/CP—1999-208916/VOL1

1998 NASA Seal/Secondary Air System Workshop

July 1999

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1998 NASA Seal/Secondary Air System Wokshop

Proceedings of a conference held at and sponsored by
NASA John H. Glenn Research Center at Lewis Field
Cleveland, Ohio
October 22–23, 1998

National Aeronautics and
Space Administration

Glenn Research Center

July 1999

Note that at the time of printing, the NASA Lewis Research Center was undergoing a name change to the NASA John H. Glenn Research Center at Lewis Field. Both names appear in these proceedings.

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Executive Summary
Volume I

The 1998 NASA Seal/Secondary Air System Workshop was divided into three major areas with limited materials presented in Volume II: (1) overviews of the (NASA's high speed research (HSR) and DOE's advanced turbine engine systems (ATS)) gas turbine programs and the general aviation program (GAP) with emphasis on sealing methods and results; (2) sealing concepts and methods and results including experimental facilities and numerical predictions; and (3) reviews of the numerical engine simulation and aerospace vehicles and concepts (Trailblazer, Bantam, and X-38). Overviews of the HSR and ATS work provide the reader with a look into large engine systems that consume from 800 to 1500+ lbs/sec of air. While the HSR program has been redirected, the ATS program continues on course and on target. The ATS program uses aeroderivative technologies to develop several new technologies that boost the power plant combined cycle efficiencies to 60 percent with a long range vision of fuel cell toping efficiencies to 80 percent while reducing the cost of electricity to the consumer. The major players are GE and Siemens-Westinghouse. On the opposite end of the size/weight scale, one finds the GAP. Teledyne 200-hp-IC 4 cylinder liquid-cooled diesel represents propeller driven private aviation while Williams 700-lb-thrust, 100-lb jet engine with a bypass ratio of 4 represents the private jet plane industry. Several seal companies provided updates on sealing technologies, yet most presentations are characterized by face seal configurations, many without the use of carbon or brush seals. Still carbon face seals are the industry workhorse but have problems with face blisters. The blisters spall and the seal fails. Blister resistent carbons have fine grains and new carbons are being readied for market. The floating brush seal works successfully at lower surface speeds while tribological tuft tests vindicate the use of Haynes-25-Chrome Carbide tribopair and comparisons to other materials are provided. Successful demonstration of the rope-seals to extreme temperatures for short duration periods provide a new form of very high temperature static seals. Leaf, reinforced cloth, face and brush sealing concepts proposed or used in industrial (aeroderivative) gas turbines show promise in increasing efficiency with long life. Intershaft sealing for turbomachines and foil bearing concepts are being developed. Interactive cavity and blade/vane time accurate numerical simulations are necessary for accurate performance, secondary and purge air management. Numerical codes and methods are now capable of providing engine performance and analysis simulations (NPSS). Aerospace programs that require advanced sealing concepts to fly include Trailblazer (subscale, suborbit RBCC demonstrator); Bantam ($1k/lb-payload in 10 years study concepts); and X-38 thermal protection systems.

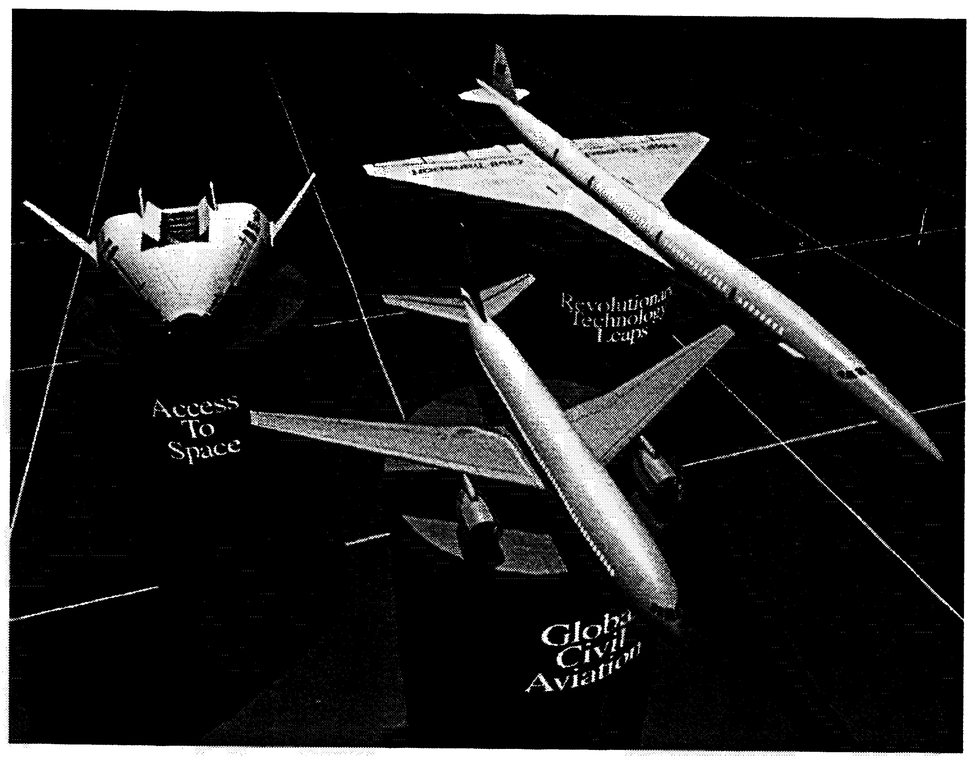
TABLE OF CONTENTS
Volume I

OVERVIEW OF THE HSR PROPULSION PROGRAM

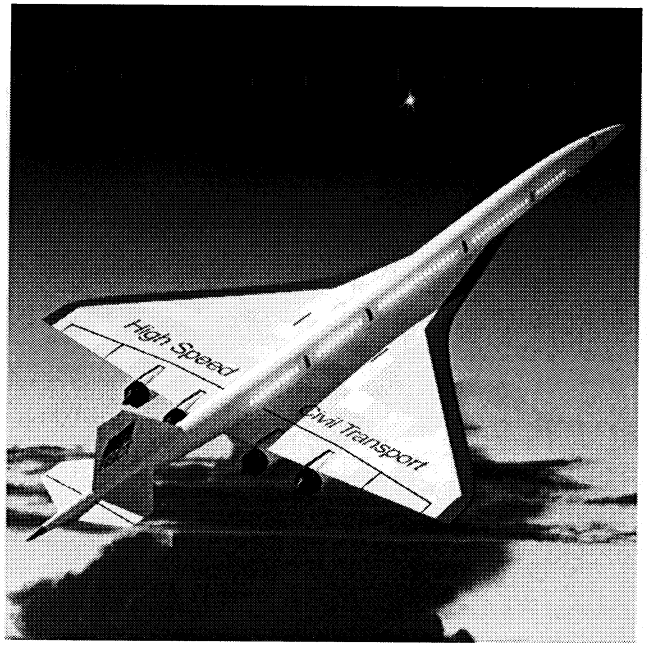
Catherine Peddie
NASA Glenn Research Center
Cleveland, Ohio

Three Pillars for Success

NASA's Response to Achieve the National Priorities in Aeronautics and Space Transportation



Goals for Pillar Two
Revolutionary Technology Leaps



Research to revolutionize air travel: environmentally friendly transoceanic supersonic flights; technology to dramatically improve small aircraft designs, engine, and overall affordability

- **Reduce the travel time to the Far East and Europe by 50 percent within 20 years, and do so at today's subsonic ticket prices**
- **Invigorate the general aviation industry, delivering 10,000 aircraft annually within 10 years, and 20,000 aircraft annually within 20 years**
- **Provide next-generation design tools and experimental aircraft to increase design confidence, and cut the development cycle time for aircraft in half**

HSR Vision

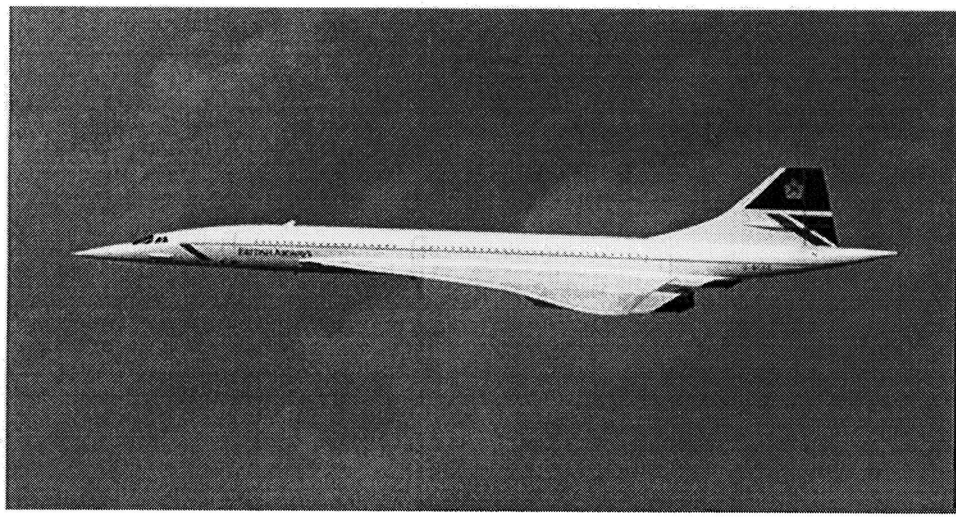
Establish the technology foundation to support the U.S. transport industry's decision for production of an environmentally acceptable, economically viable, 300-passenger, 5000 n.mi, Mach 2.4 aircraft.

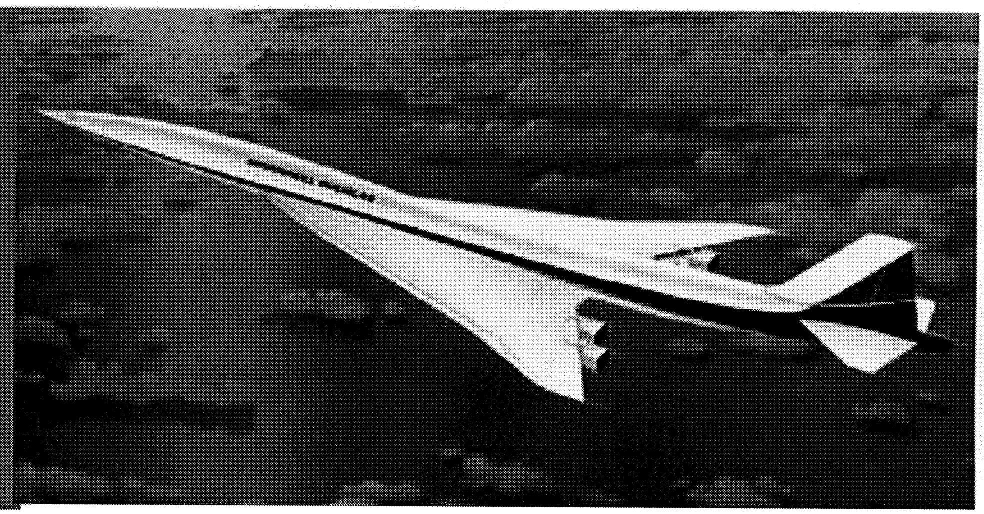
HSR Propulsion Mission

Provide the U.S. aeropropulsion industry with the critical component, enabling engine materials, and full scale system technologies to allow industry's decision on production of an environmentally acceptable, economically viable, 300-passenger, 5000 n.mi., Mach 2.4 aircraft.

Work with the corresponding airframe management team to assure overall HSR project success.

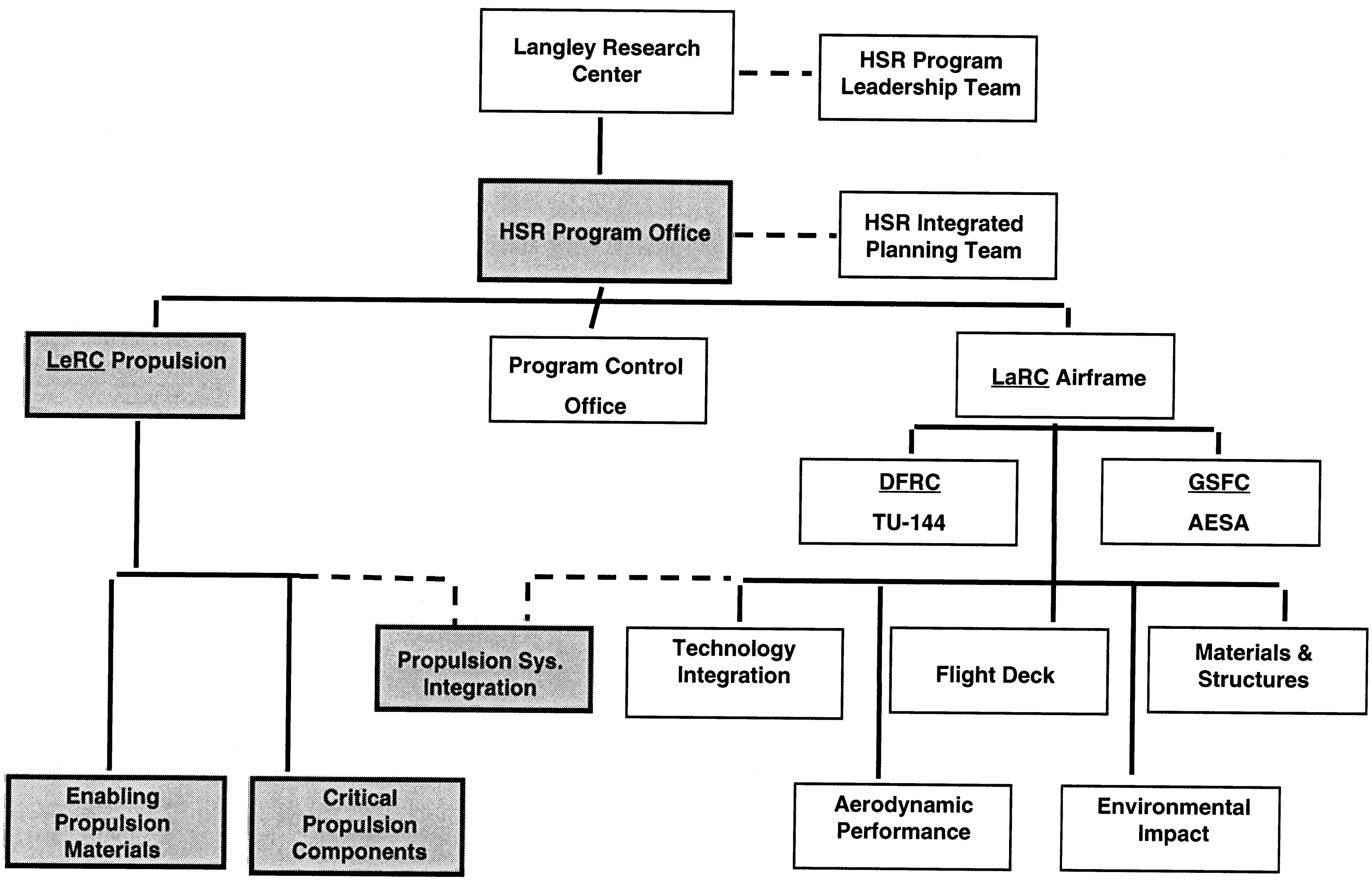
Concorde vs. the High Speed Civil Transport

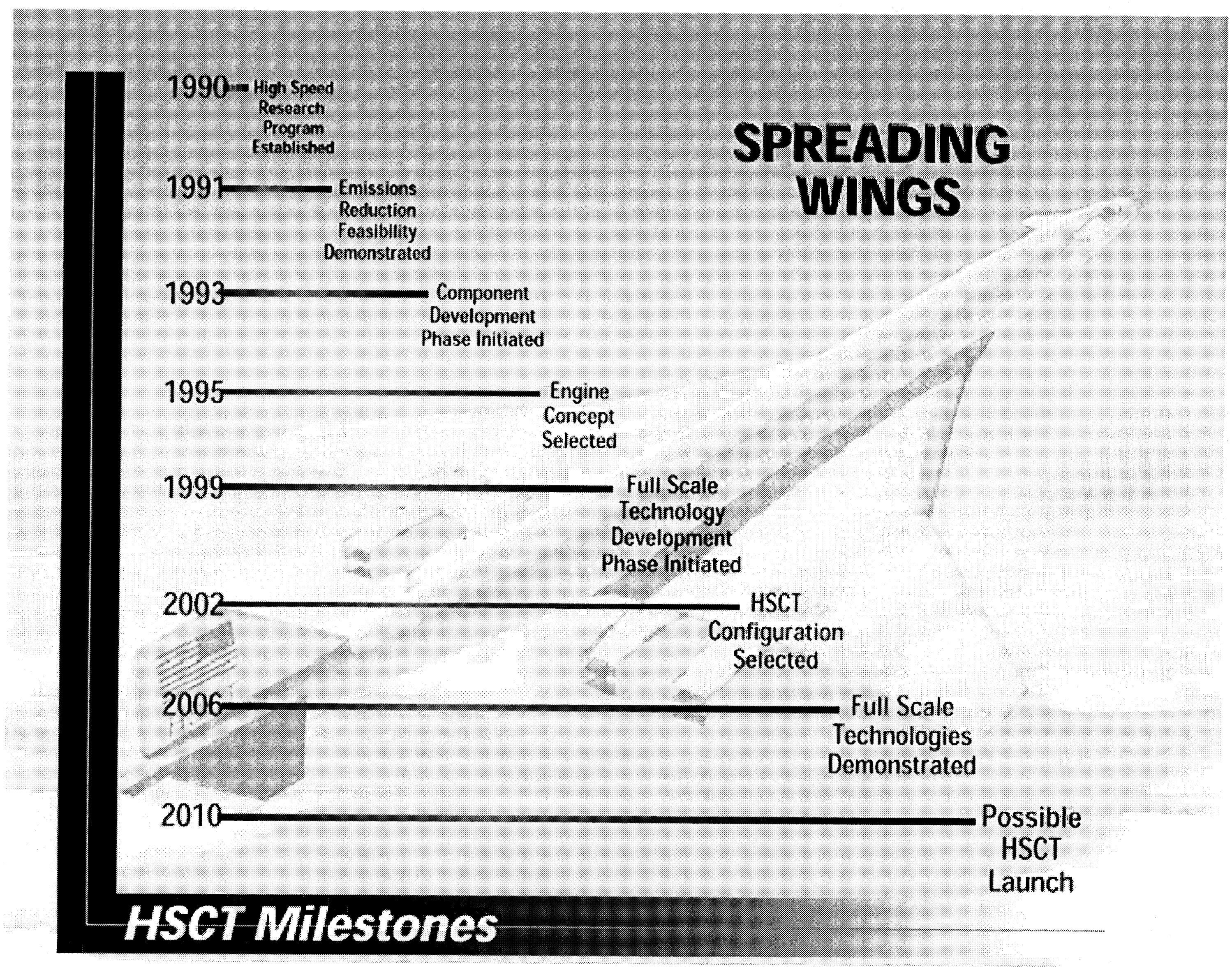




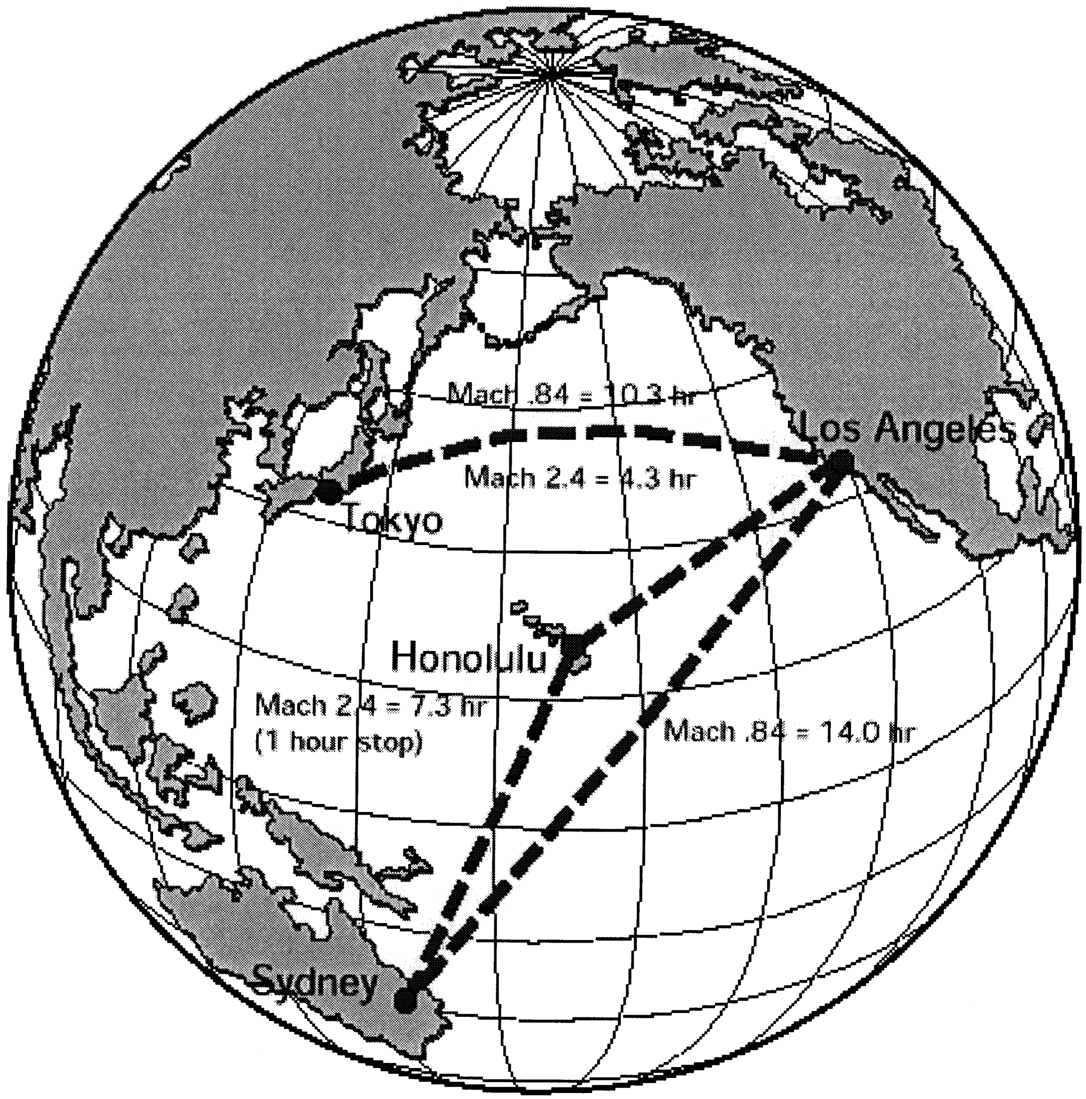
Concorde		HSCT
3,000	Range (n. mi.)	5,000 - 6,500
128	Payload (passengers)	250 - 300
400,000	Weight (lb.)	750,000
Excempt	Community Noise Std.	FAR 36 Stage III - x dB
Premium	Fare Levels	Standard + " 20% Premium
20	NOx, Emission Index	5

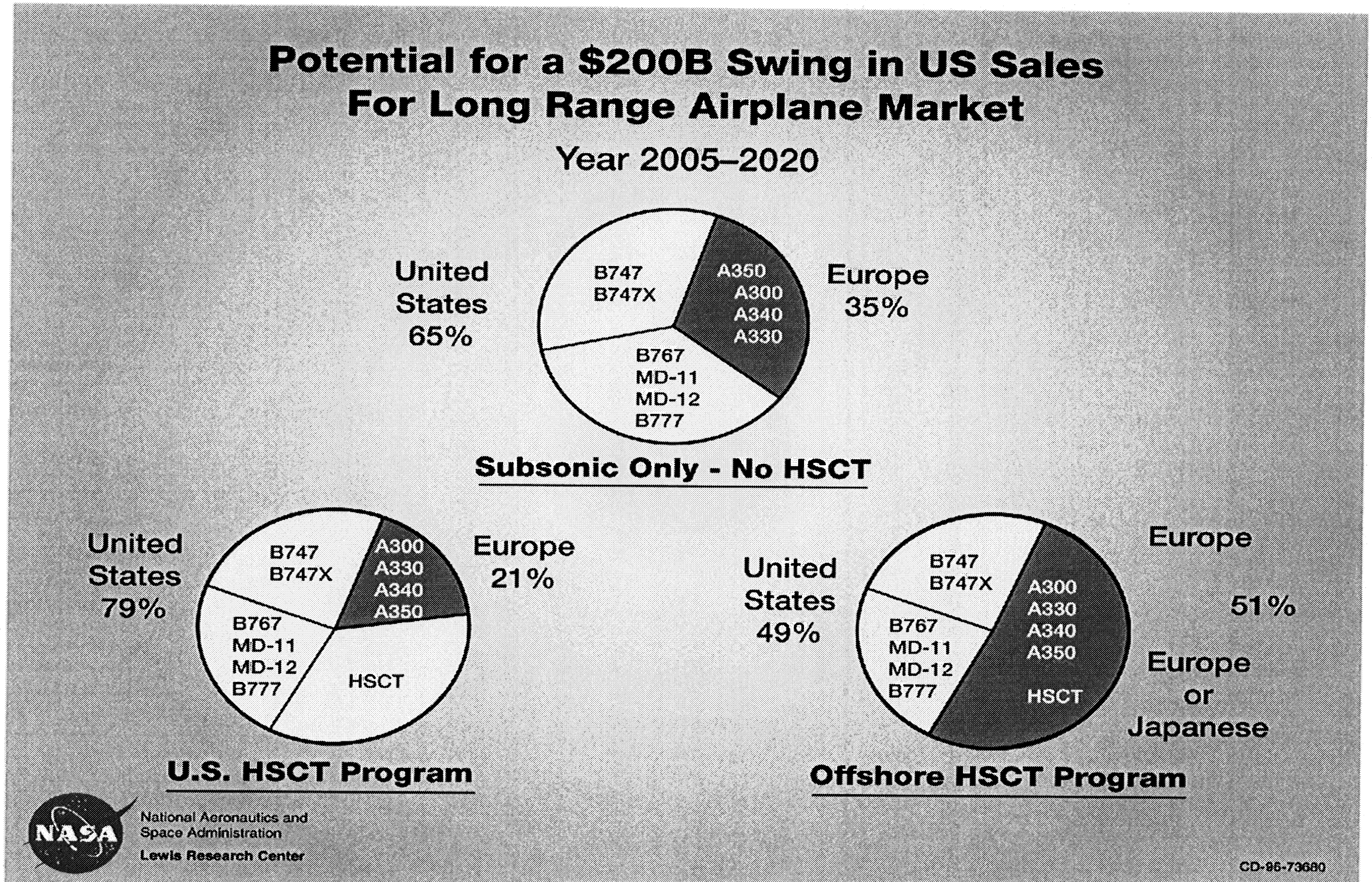
HSR Project Structure




SPREADING WINGS
1990 High Speed Research Program Established
1991 Emissions Reduction Feasibility Demonstrated
1993 Component Development Phase Initiated
1995 Engine Concept Selected
1999 Full Scale Technology Development Phase Initiated
2002 HSCT Configuration Selected
2006 Full Scale Technologies Demonstrated
2010 Possible HSCT Launch
HSCT Milestones

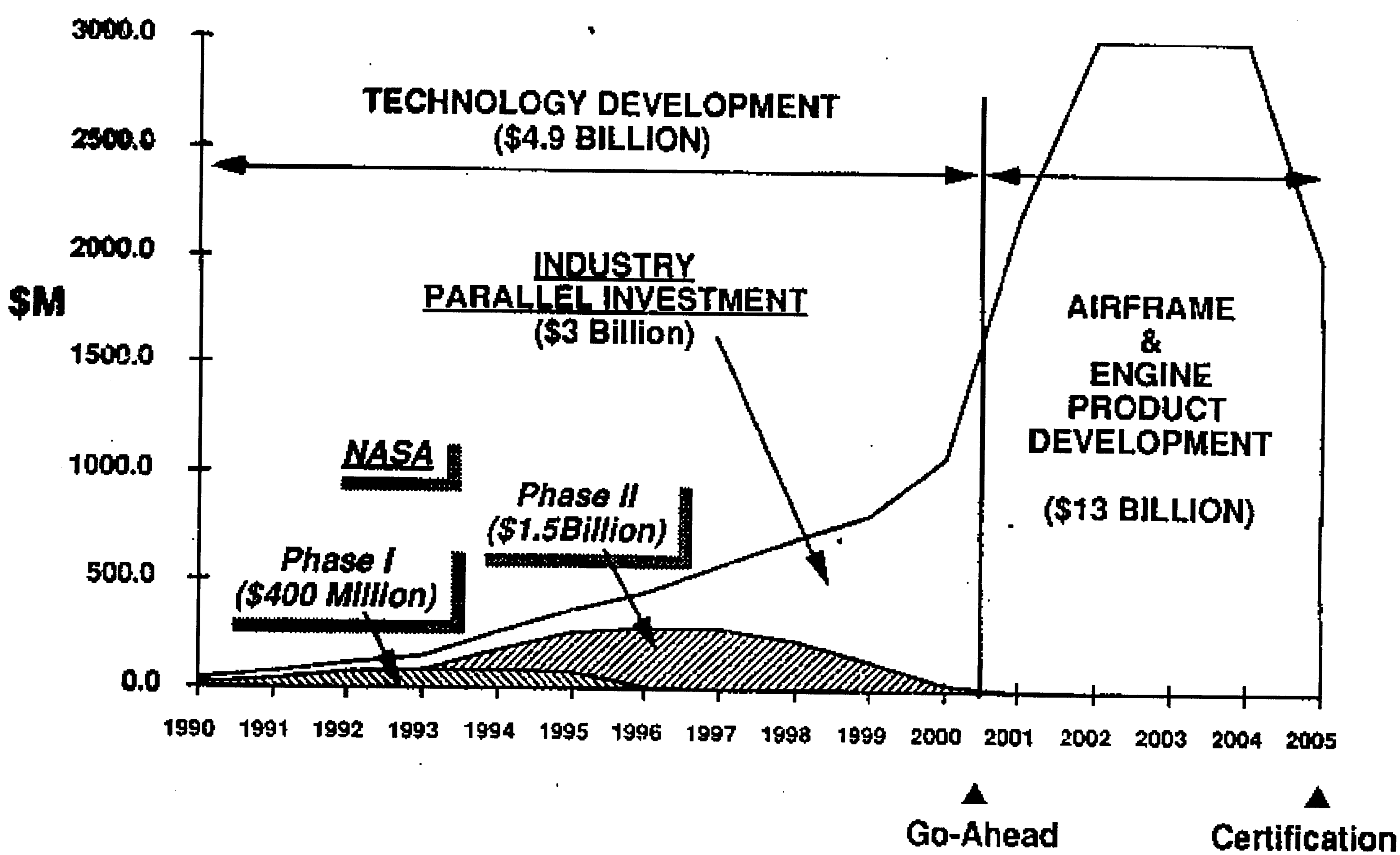
A SMALL WORLD




Potential for a $200B Swing in US Sales
For Long Range Airplane Market
Year 2005–2020
United States 65%
B747
B747X
A350
A300
A340
A330
B767
MD-11
MD-12
B777
Europe 35%
Subsonic Only - No HSCT
United States 79%
B747
B747X
A300
A330
A340
A350
B767
MD-11
MD-12
B777
HSCT
Europe 21%
U.S. HSCT Program
United States 49%
B747
B747X
A300
A330
A340
A350
HSCT
B767
MD-11
MD-12
B777
Europe
51%
Europe or Japanese
Offshore HSCT Program
National Aeronautics and Space Administration
Lewis Research Center
CD-96-73680

HSCT TOTAL INVESTMENT

INTEGRATED NASA/INDUSTRY NATIONAL PLAN



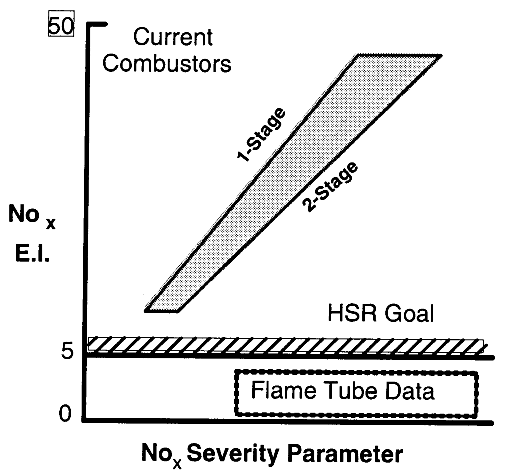
Economic Barriers: Current Economic Baseline

- From the airline standpoint
  - Ticket premium
  - Direct operating cost
  - Acquisition cost
  - Return on investment
- As the manufacturer sees it
  - Development cost
  - Manufacturing cost
  - Market size
  - Market price
- History of commercial supersonic aircraft
  - 20 Concordes built, 14 delivered to airlines
  - Concorde development cost ≈ 7.9 billion (1995$)
  - Concorde roundtrip transatlantic fare -- $8,475
  - 777 fuel burn/seat mile ≈ 20% of Concorde
  - 17 Tu-144's built, none in service today

Key Technical Challenges are Emissions, Noise and Durability

Emissions

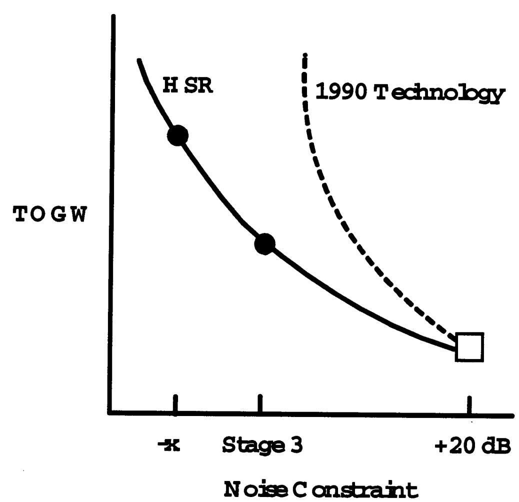
A Mach 2.4 HSCT will cruise at altitudes coincident with the highest concentration of atmospheric ozone. Advanced combustors are required to reduce NOx emissions to levels which have no significant impact on the Earth's ozone layer.



This challenge requires novel combustors and advanced materials.

Noise

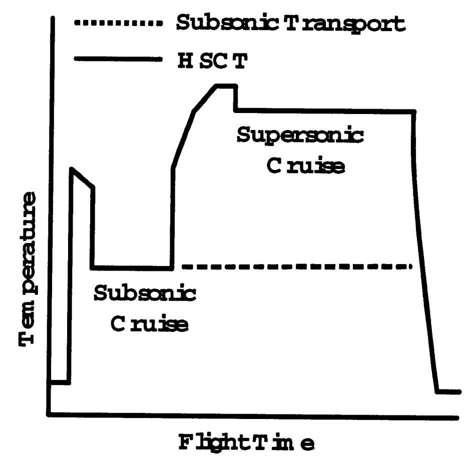
High specific thrust engines optimized for supersonic cruise have high jet velocities and are inherently noisy. Unconventional engines/nozzles are required to achieve compliance with FAR 36 Stage 3 noise regulations while providing acceptable subsonic and supersonic cruise performance.



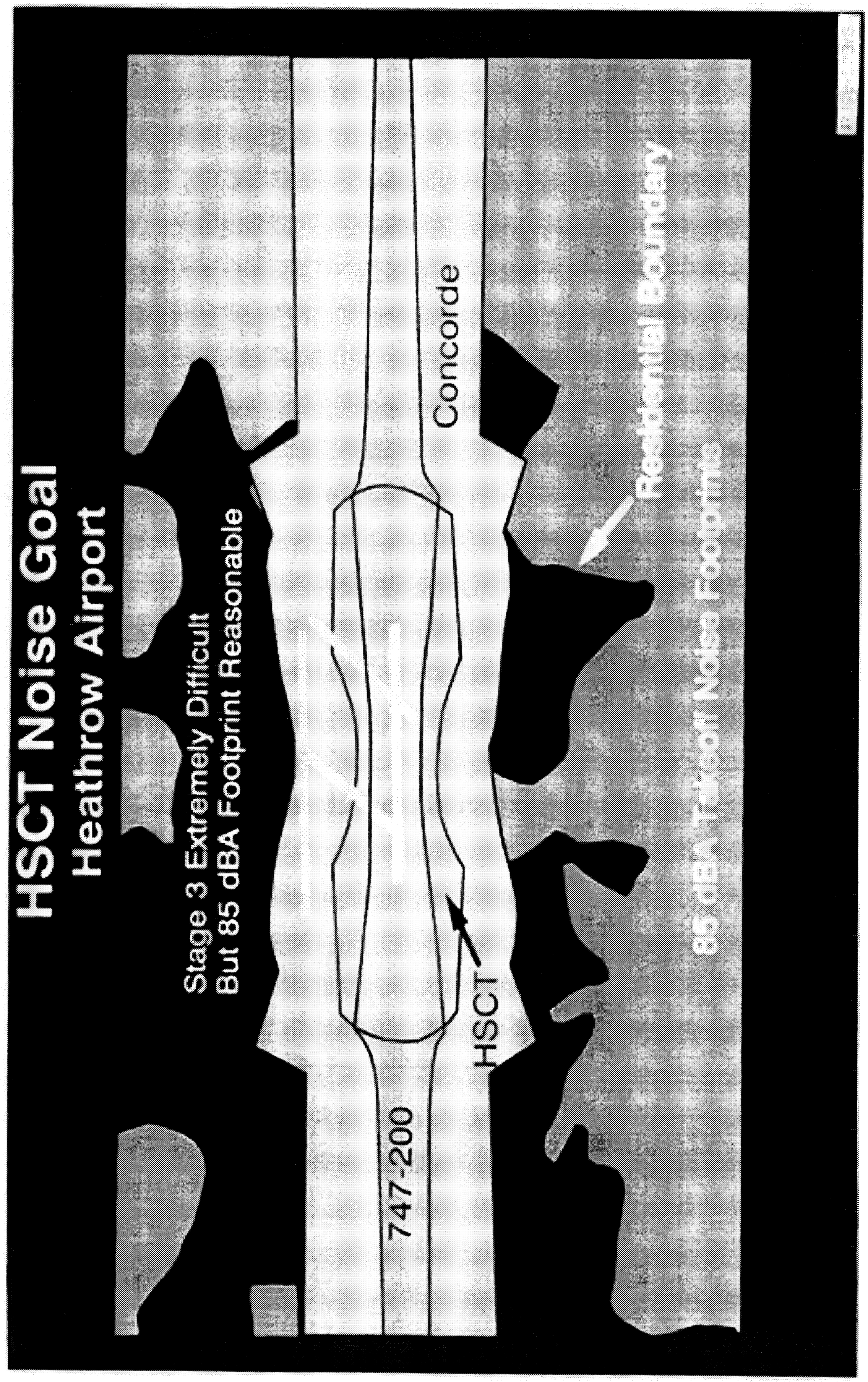
This challenge controls inlet, engine, nozzle selection.

Durability

Over their entire life, current tactical fighter and subsonic commercial transport engines accumulate 250 to 300 hours at max cycle temperatures and stress levels. HSCT propulsion systems must operate at these conditions for 9,000 hours. Thus, the HSCT duty cycle is 30X that of current engines.

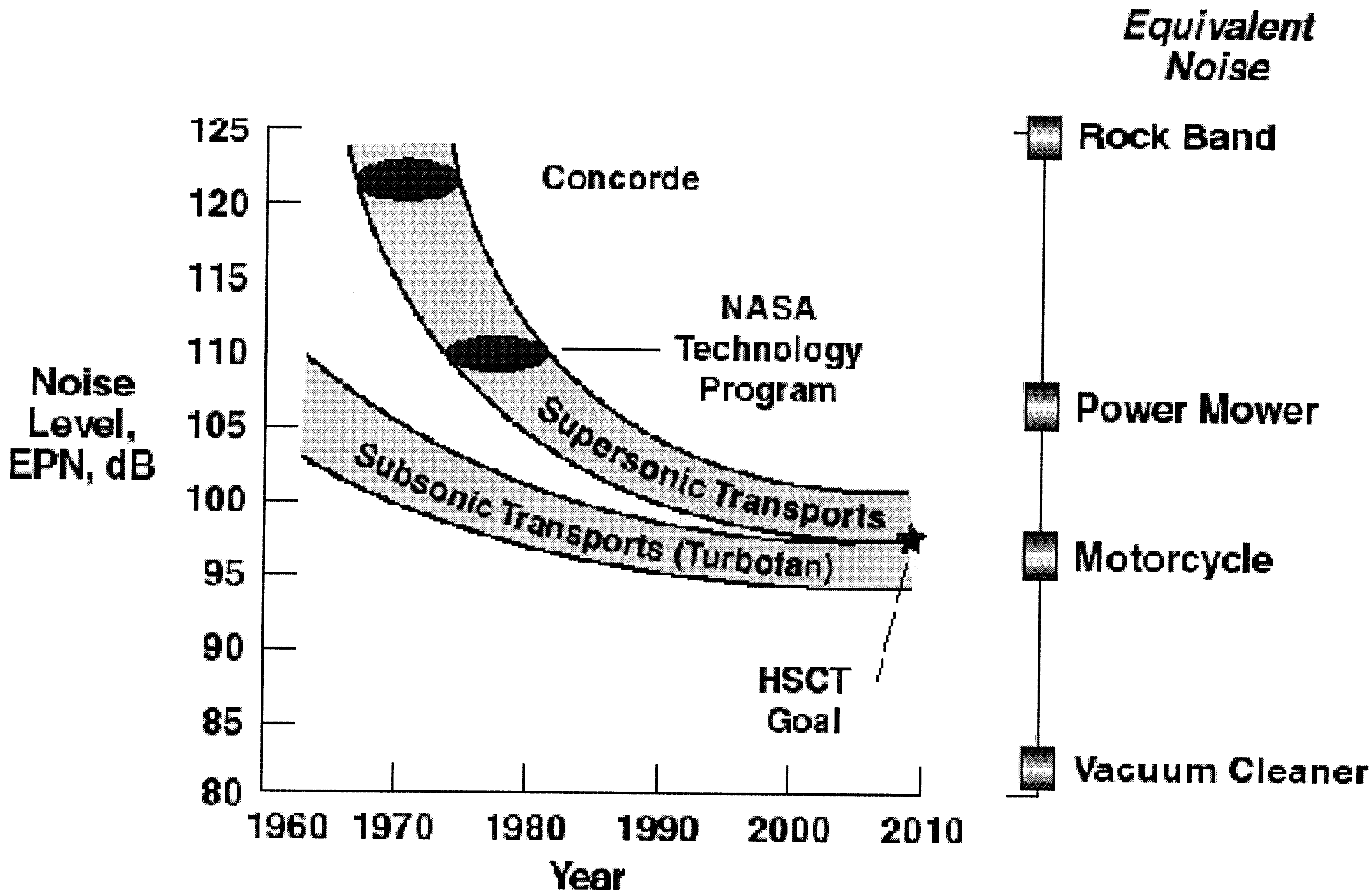


This challenge demands advanced high-temp materials and cooling schemes.

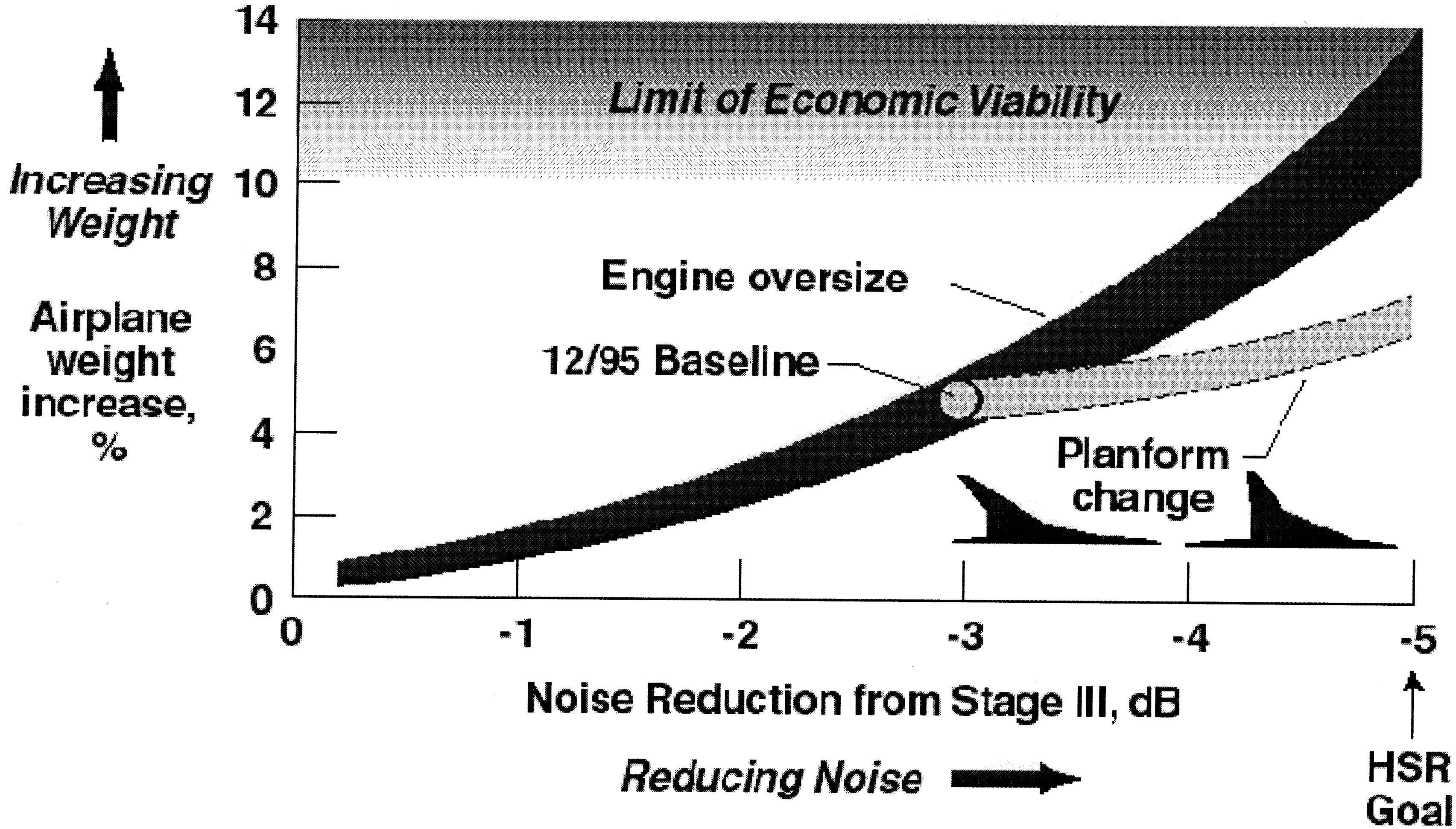


HSCT Noise Goal
Heathrow Airport
Stage 3 Extremely Difficult
But 85 dBA Footprint Reasonable
Concorde
747-200
HSCT
Residential Boundary
85 dBA Takeoff Noise Footprints

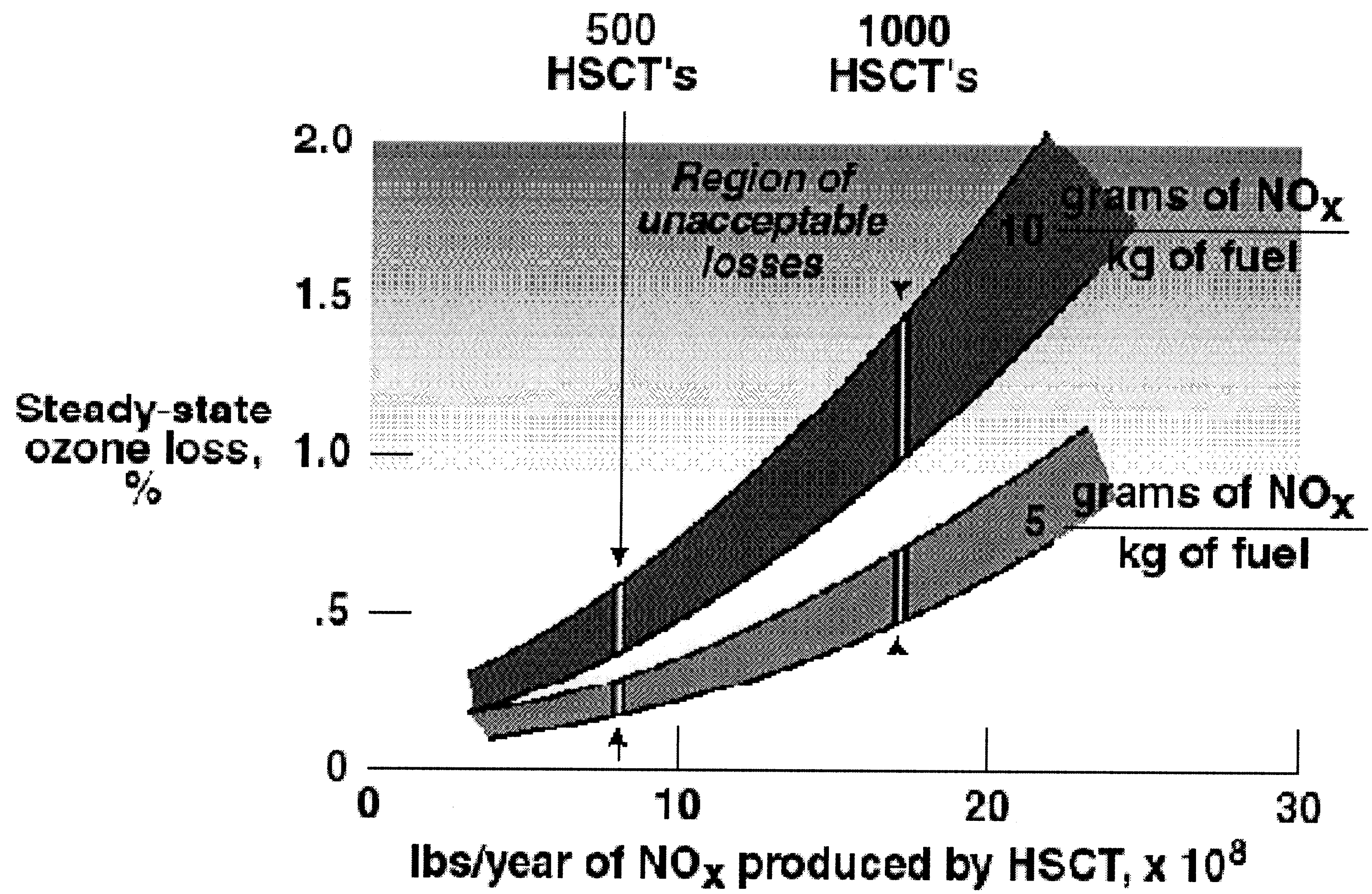
HSCT NOISE REDUCTION CHALLENGE



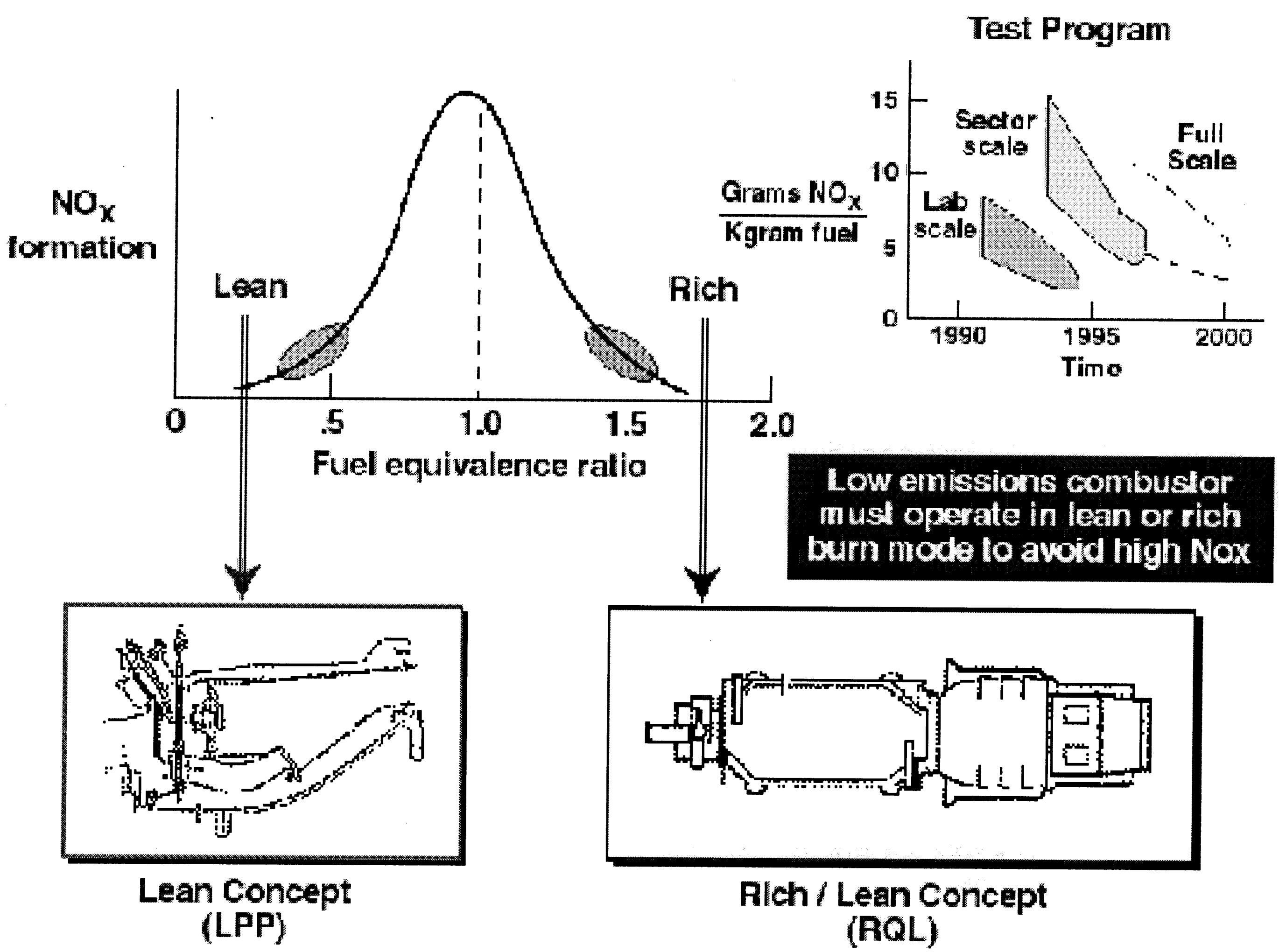
HSCT Weight Penalty for Achieving Noise Goals



OZONE LOSS vs TOTAL NO_X PRODUCTION



LOW NOx COMBUSTOR CONCEPTS



Environmental & Economic Barriers = Technical Challenges

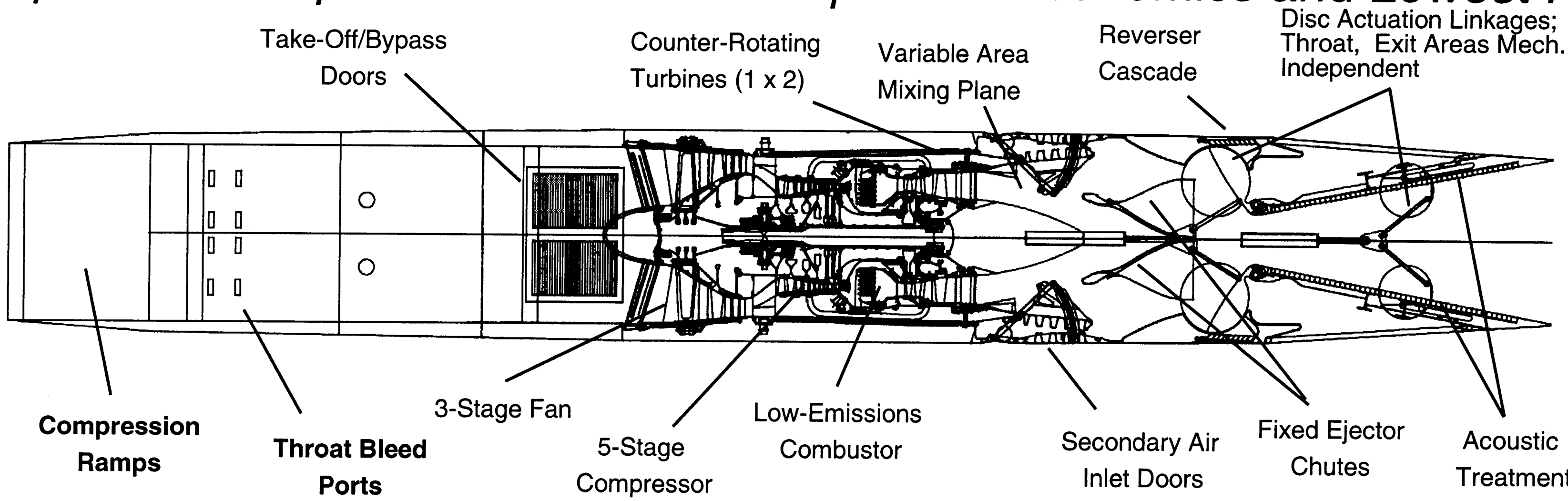
- Propulsion System Challenges
  - Ultra low NOx emissions levels assure no adverse impact to the Earth's ozone layer
  - Community noise levels (takeoff, cutback, approach) equal to or lower than the subsonic fleet
  - High temperature engine/nozzle materials which have acceptable characteristics for durability, weight, performance, and safety when incorporated in an HSCT propulsion system design
  - Sufficient thrust needed to combat the extra drag of supersonic flight while minimizing transonic and supersonic fuel burn

Near-term Technical Solutions: Propulsion System Advances

- High specific thrust cycles for efficient supersonic cruise which simultaneously achieve compliance with at least FAR 36 Stage 3 noise regulations
- Ultra-low Nitric Oxide emissions combustors
- High performance mixed-compression inlets with high stability margins for safe operation
- 30 fold increase in operating time at maximum temperatures and stresses over current commercial and military engines

HSCT Inlet/Engine/Nozzle System

Propulsion Components Selected for Optimum Economics and Lowest Risk



2D Bifurcated Mixed-Compression Inlet

- Lowest overall risk
- Low mechanical complexity
- Lightest weight when required acoustic treatment area is included

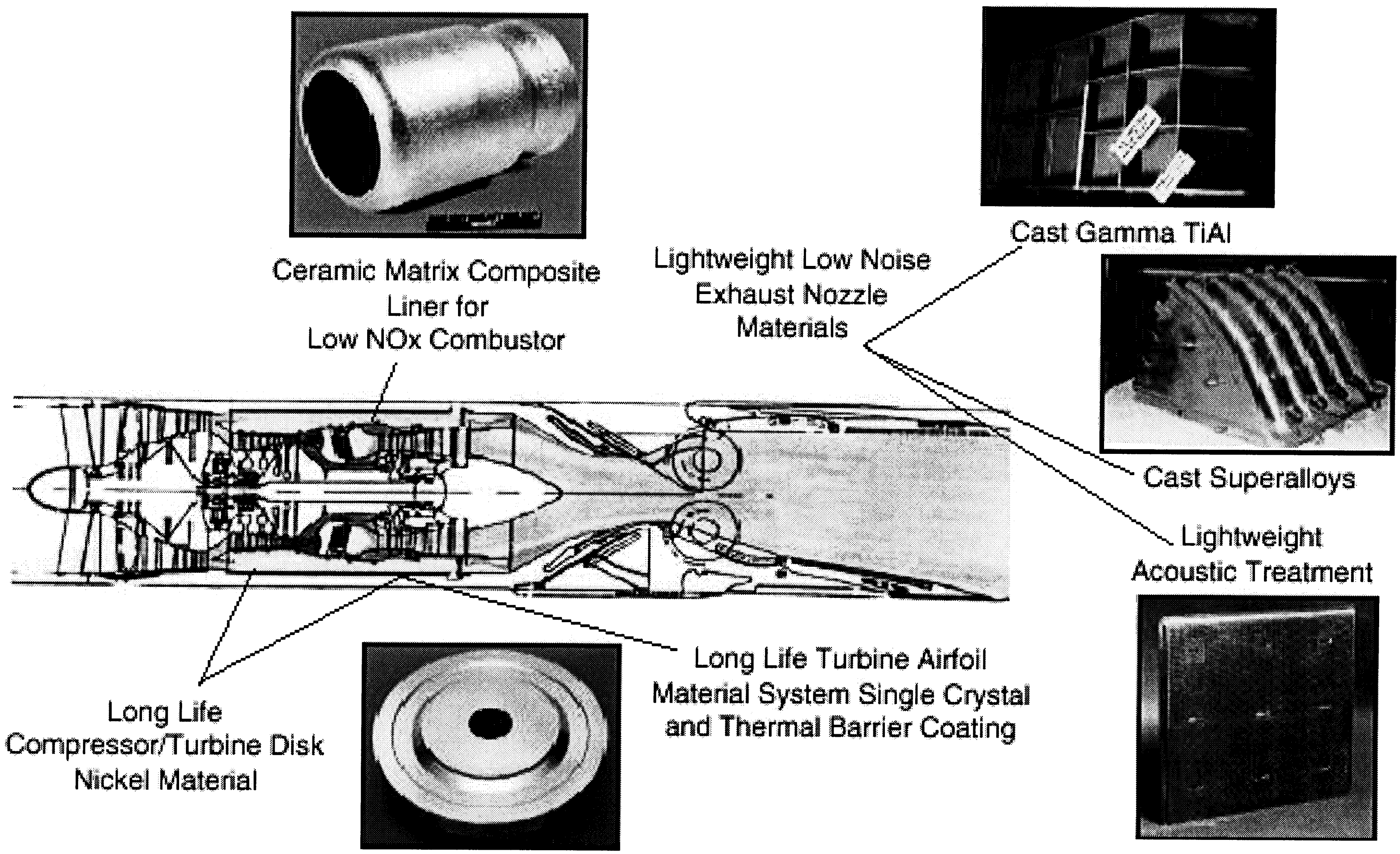
Mixed-Flow Turbofan Engine

- Moderate-risk, conventional turbomachinery
- Flexibility to match aircraft thrust requirements and noise suppression limitations

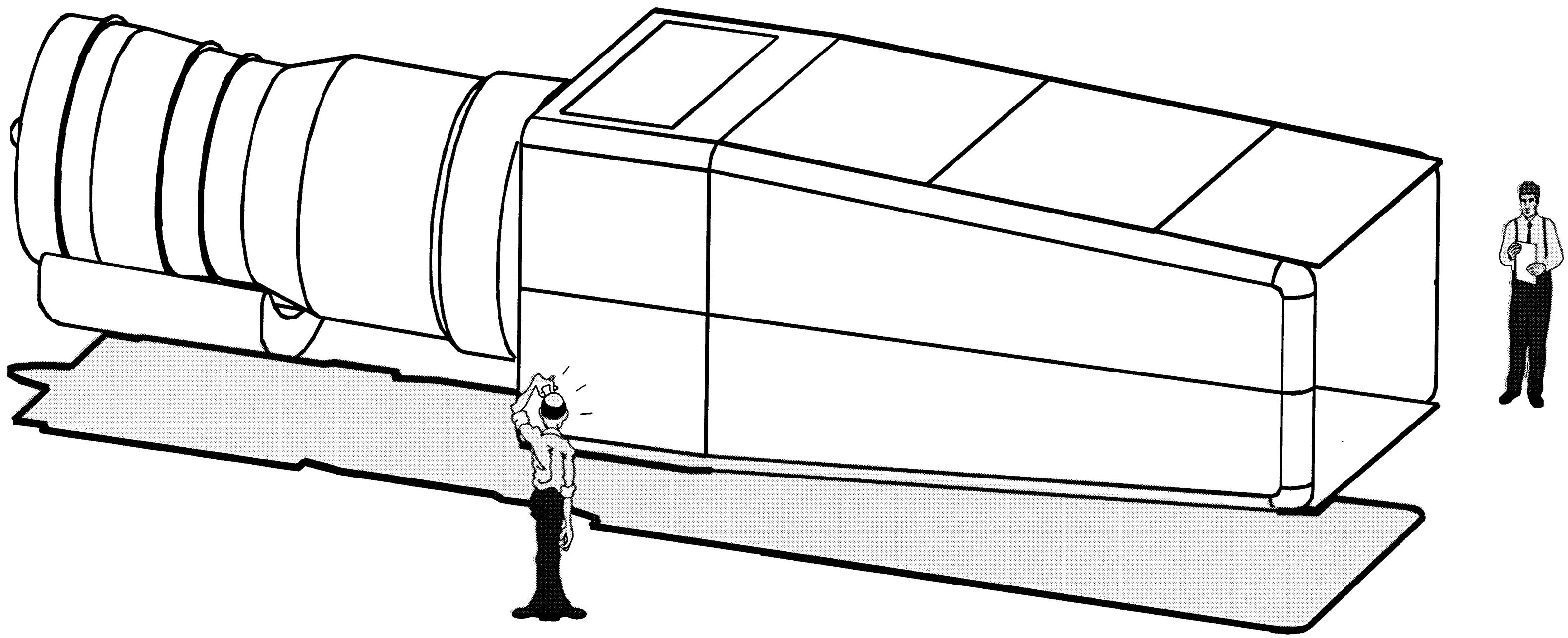
2-D Mixer-Ejector Exhaust Nozzle

- Moderate-risk noise suppression concept
- Avoids over-sizing of inlet and engine

- Propulsion Technology Concept selection met HSR Level 1 milestone
  - Lowest take-off gross weight, most economically attractive vehicle

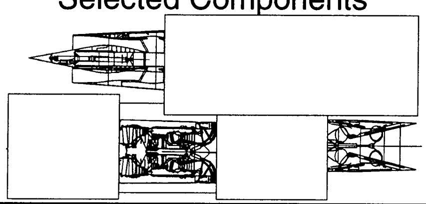
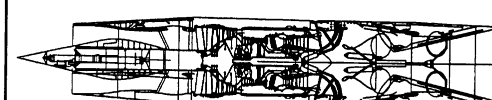

Ceramic Matrix Composite
Liner for
Low NOx Combustor
Lightweight Low Noise
Exhaust Nozzle
Materials
Cast Gamma TiAl
Cast Superalloys
Lightweight
Acoustic Treatment
Long Life Turbine Airfoil
Material System Single Crystal
and Thermal Barrier Coating
Long Life
Compressor/Turbine Disk
Nickel Material

HSCT Engine Part Sizes Approach Manufacturing Limits



- Forging Limits For Fan And Compressor Blisks & Turbine Disk
- Heat Treatment For Thick Bore Turbine Disks
- Casting of Large Size Turbine Airfoils With Complex Internal Features
- Casting of Large Size, Thin Wall Nozzle Components
- Fabrication of Large Diameter Ceramic Matrix Composite Combustor Liners

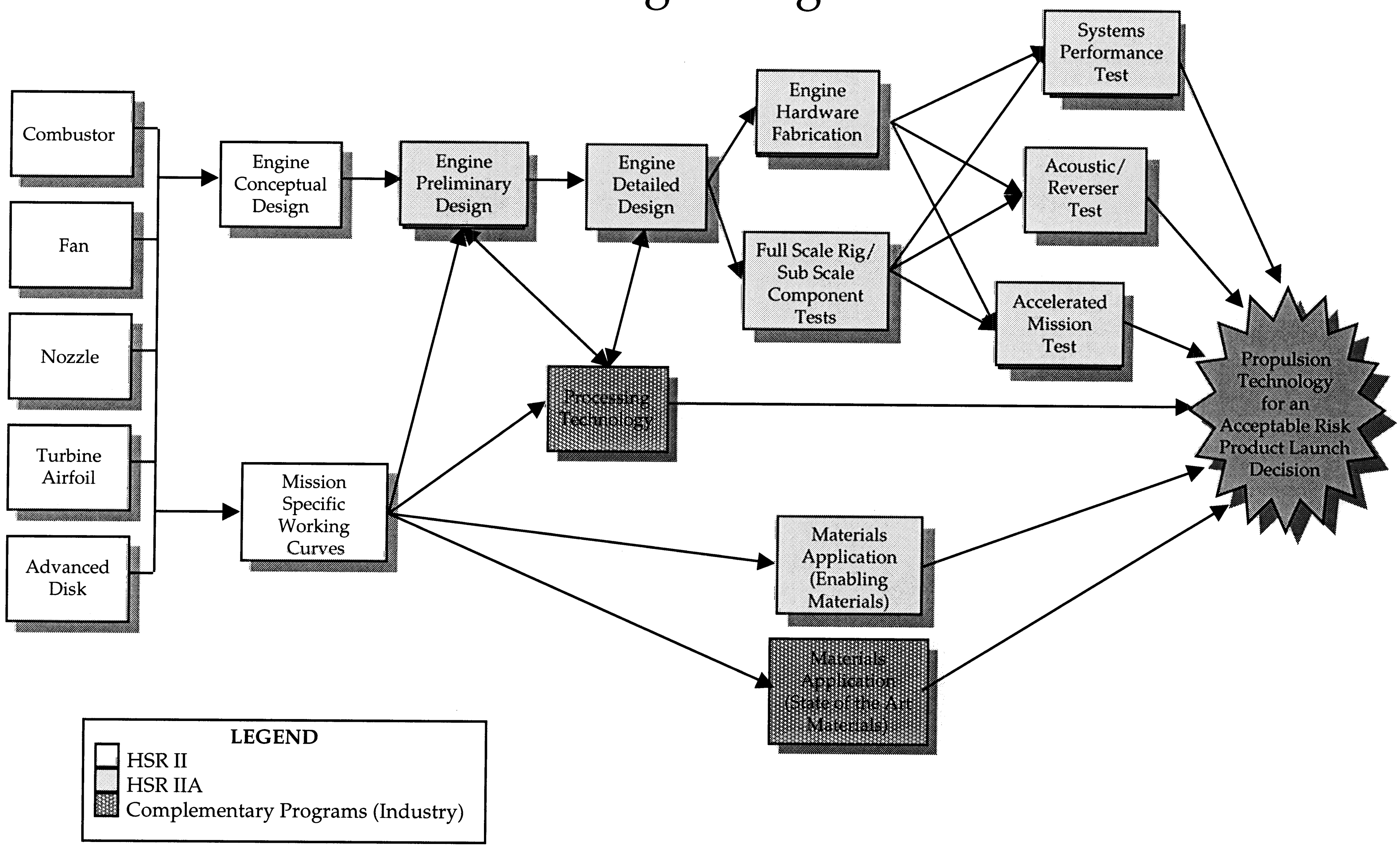
Propulsion Development Path

	HSR II NASA/Industry Partnership	HSR IIA NASA/Industry Partnership	Product Development Industry
Focus	Technology Development	Full Scale Technology Demonstration/Validation	Product Launch/Development
Environmental Barrier Issues	Sub-Scale Concept Demonstration	Full Scale Configuration Validation	Propulsion System Certification
Propulsion System Materials	Enabling Materials Selection and Development	Enabling Materials Application	Production Materials and Processes
Fabrication Processes	Laboratory/Test Cell Processes	Pre-Production Processes	Production Processes
Articles Fabricated	Selected Components 	Full Scale Engine and Exhaust Nozzle 	Propulsion System Assemblies 
Extent of Testing	Subscale and Selected Full Scale Demonstration of Technologies	Full Scale Engine Demo Tests (SMP, Acoustic, AMT Method Validation)*	Propulsion System Endurance and Certification
Cost Basis	Industry/NASA Cost Trades	Industry/NASA Cost Trades	Production Costs, Business Plan

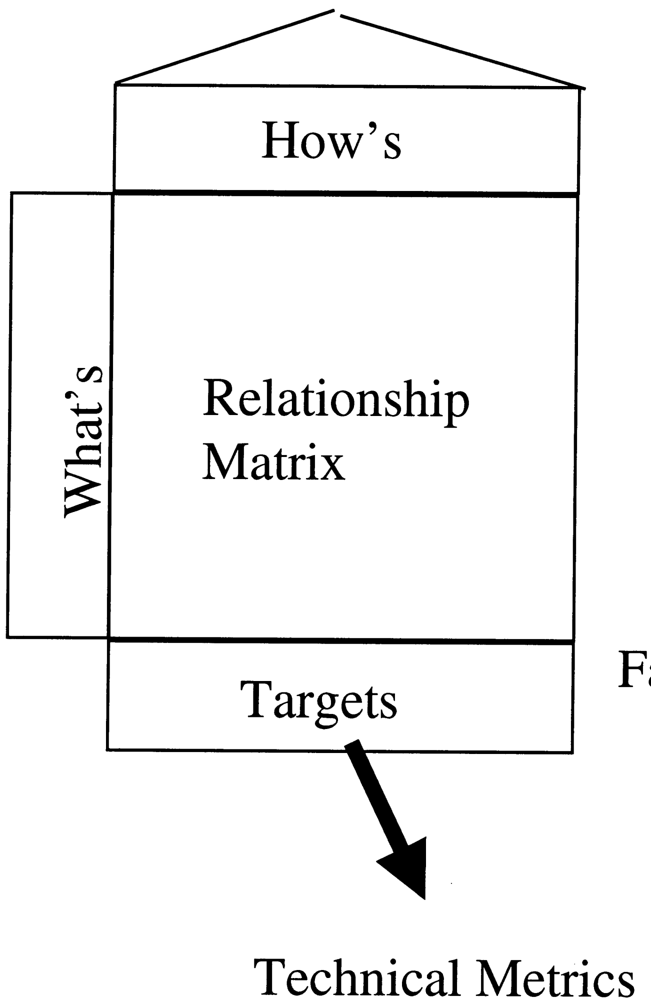
* Note: SMP=System Mechanical Performance
AMT=Accelerated Mission Test

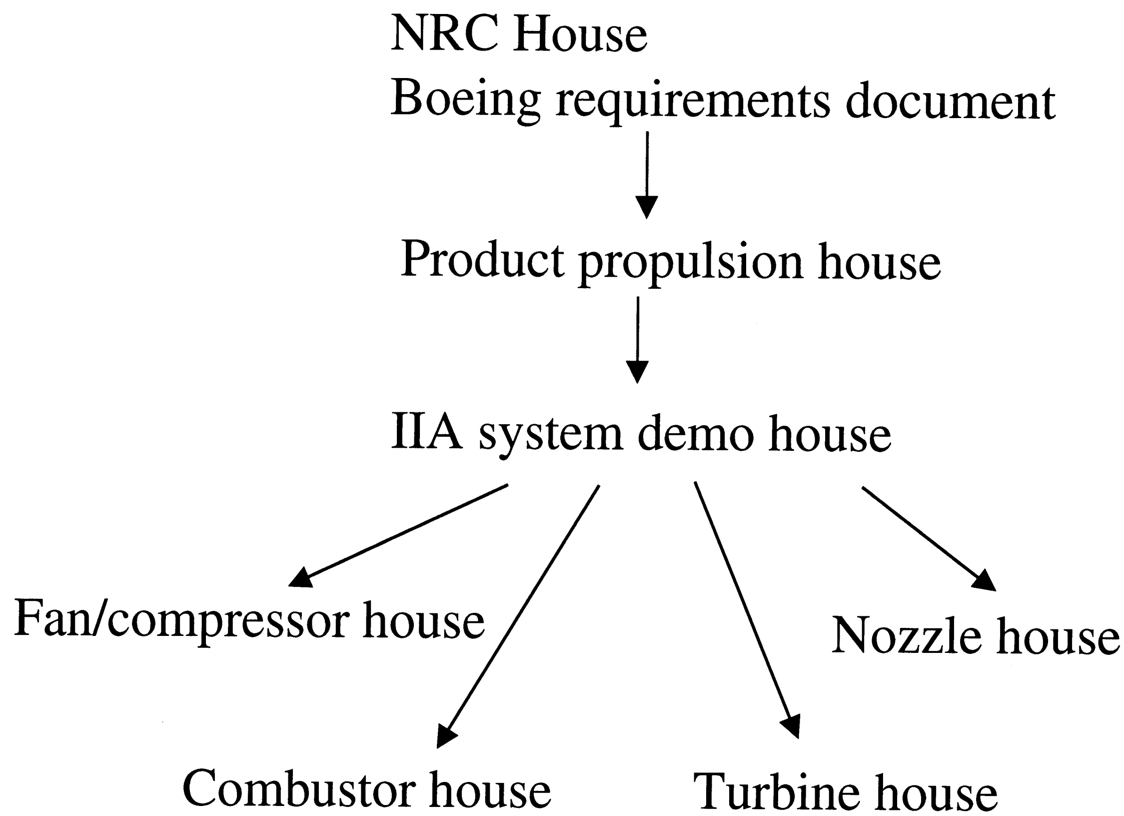
Full Scale Engine/Nozzle Technology Demonstrator

Overall Logic Diagram



QFD-The "House of Quality" -Applied to HSR Propulsion





QFD process yields a consistent set of technical metrics driven by system requirements.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Tu-144LL SUPERSONIC FLYING LABORATORY

SUPERSONIC CRUISE PROPULSION RESEARCH

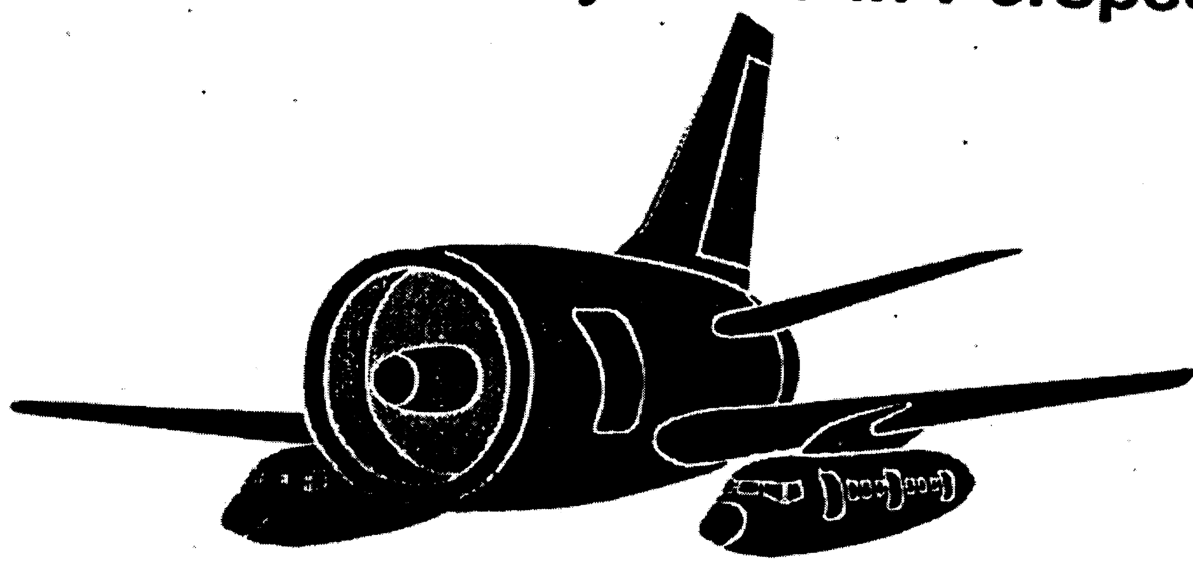
SYSTEMS STUDIES
- Variable cycle engines
- Supersonic through flow fan engines

FOCUSED TECHNOLOGY PROGRAMS
- Environmental concerns
  - ▲ NO_x emissions
  - ▲ Community noise
- Supersonic through flow turbomachinery
  - ▲ Fan stage
  - ▲ Inlets
- Conventional supersonic inlets
- Enabling propulsion materials

FUNDAMENTAL R&T
- Analysis codes
  - ▲ Inlet
  - ▲ Supersonic fan
  - ▲ Combustor
  - ▲ Nozzles (aero/acoustic)
- Fluid physics
  - ▲ Shear flow control
  - ▲ Fundamental aeroacoustics

CD-90-51195

New Propulsion Systems in Perspective



OVERVIEW OF THE DOE ADVANCED TURBINE SYSTEMS PROGRAM

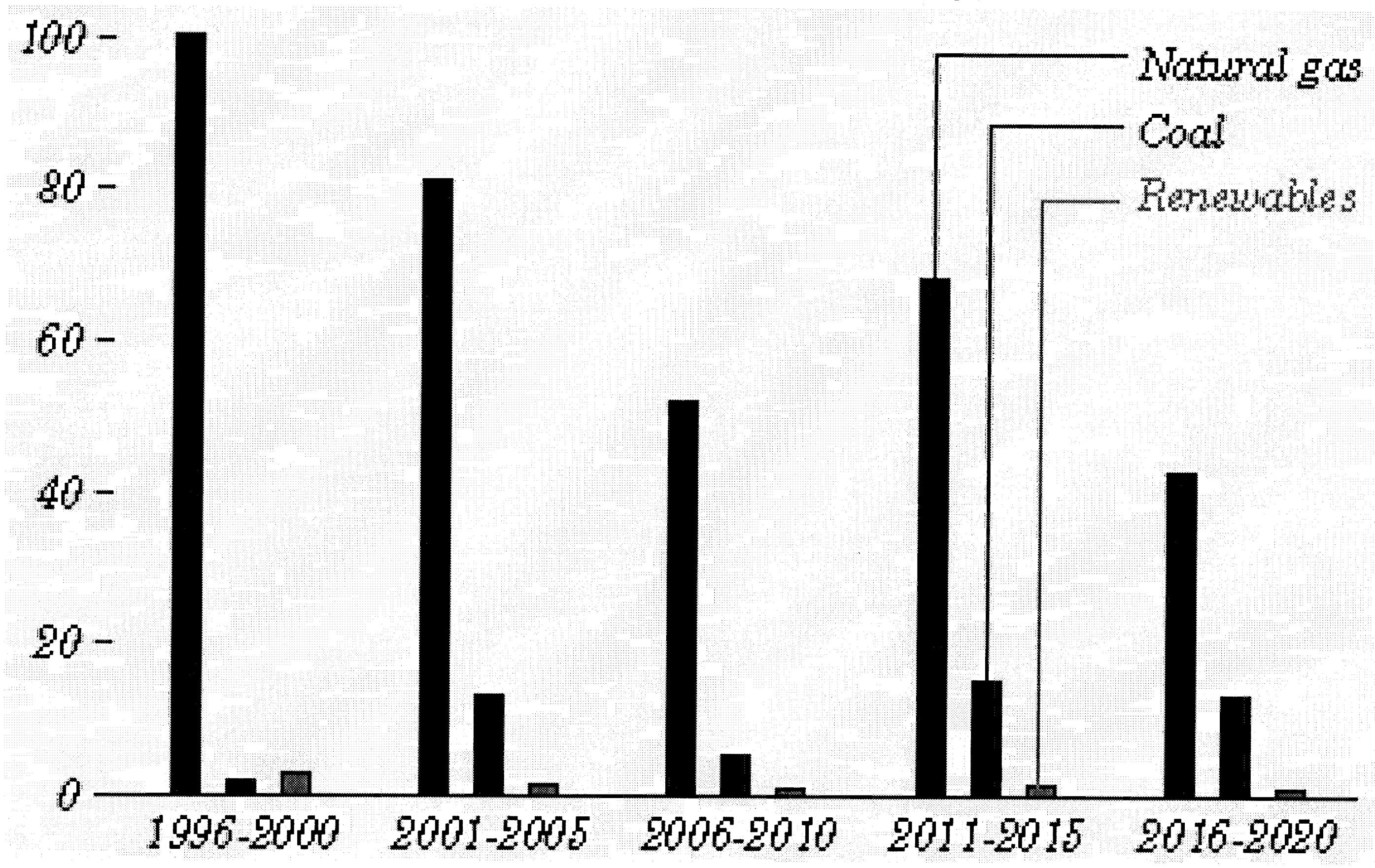
Abbie W. Layne
United Stated Department of Energy
Morgantown, West Virginia

Why develop advanced turbine systems?

- ***Market Demands*** **- Gas turbine power systems markets are rapidly growing to serve new demand, displacement or existing capacity and replacement of retired capacity**
- ***Climate Change*** **- Environmental regulations continue to require reduced levels of air pollutants from power generation facilities**
- ***DOE shares risk/accelerates public benefits***

THE NEED FOR ADVANCED GAS TURBINES WILL CONTINUE

U.S. Capacity additions by fuel type, GW



Source EIA 1998 report, fig. 57

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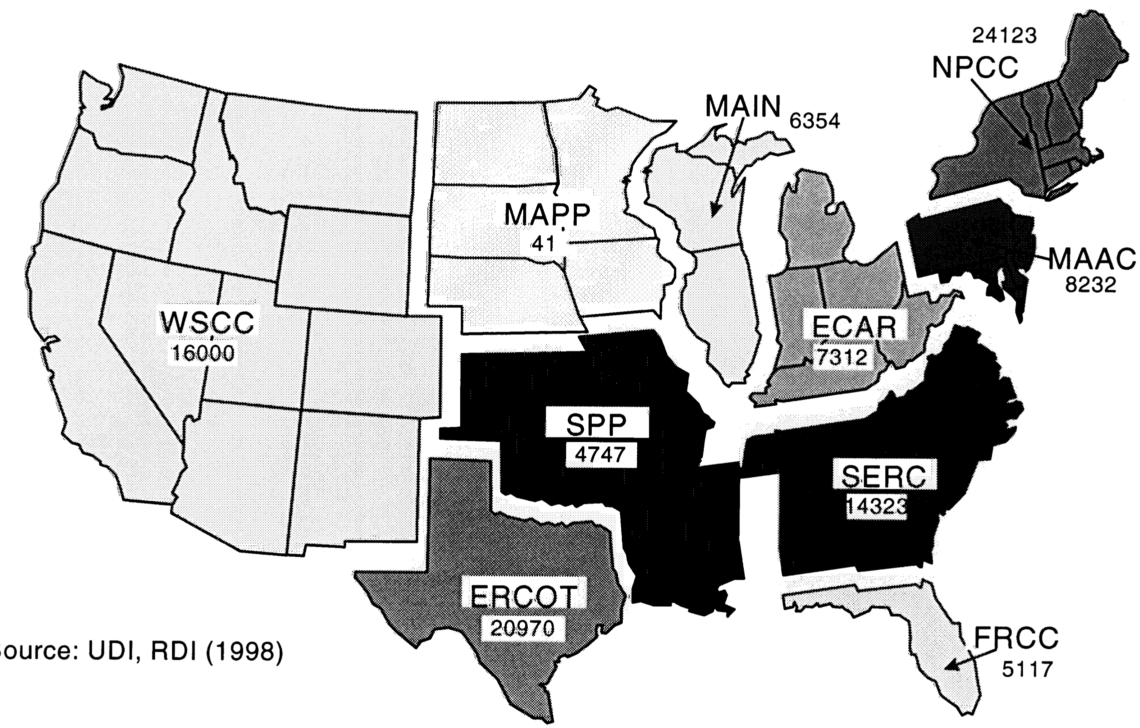
Announced Total Capacity (MW) Additions by NERC Region
(as of 9/98)



Source: UDI, RDI (1998)

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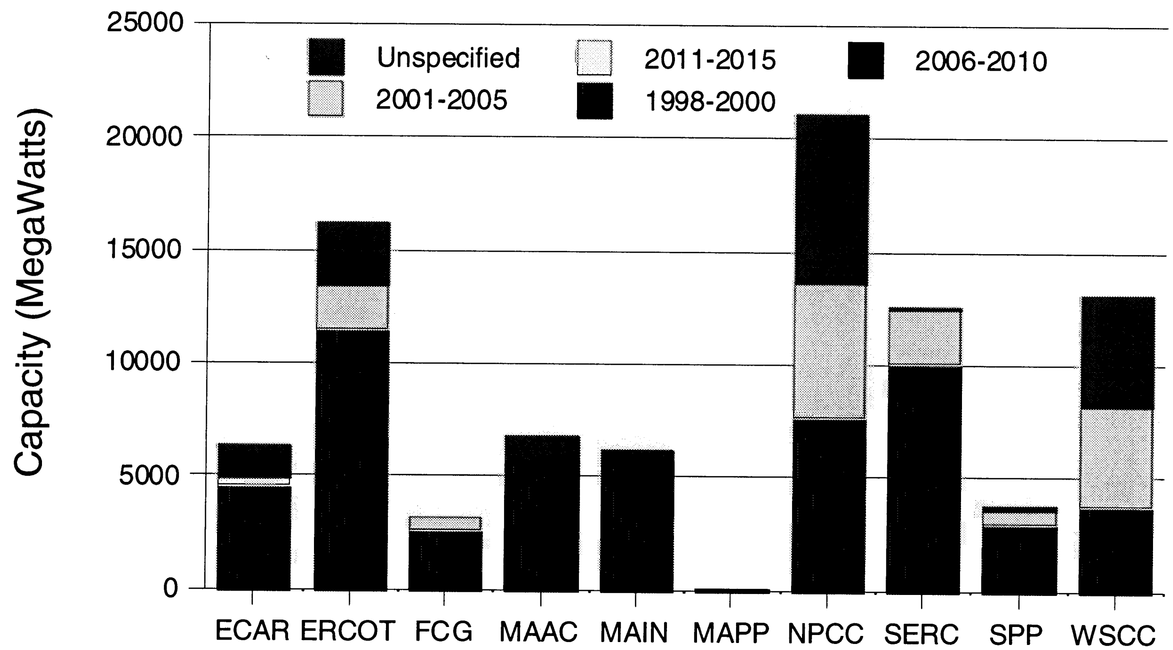
Proposed Installation Dates for Announced Gas-Fired Capacity Additions, by NERC Region (1998-2015)



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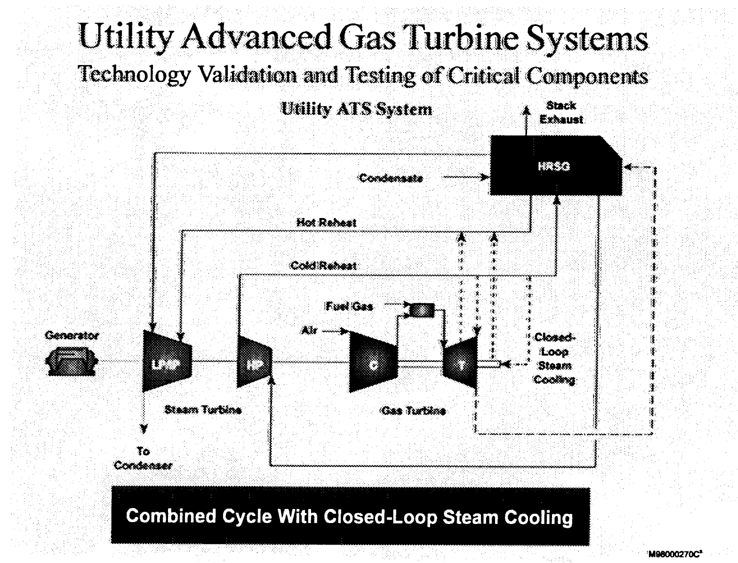
ATS-Scope of the Program

- Develop advanced turbine systems for utility-scale power generation
- Conduct supporting technology base research and development to advanced turbine systems
- 6 major projects:
  GE, Westinghouse, ORNL,
  SCIES, ABB, FETC, UTRC



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Objective: ATS Program

- **By 2000, develop ATS for utility and industrial applications that are:**

- Ultra-high efficiency:	> 60% for utility scale systems
	15% improvement for industrial system
- Super-clean:	NOx <8 ppm
- Cost of electricity	10% lower
- Fuel flexible:	Gas primary focus

Leapfrog in Turbine Performance

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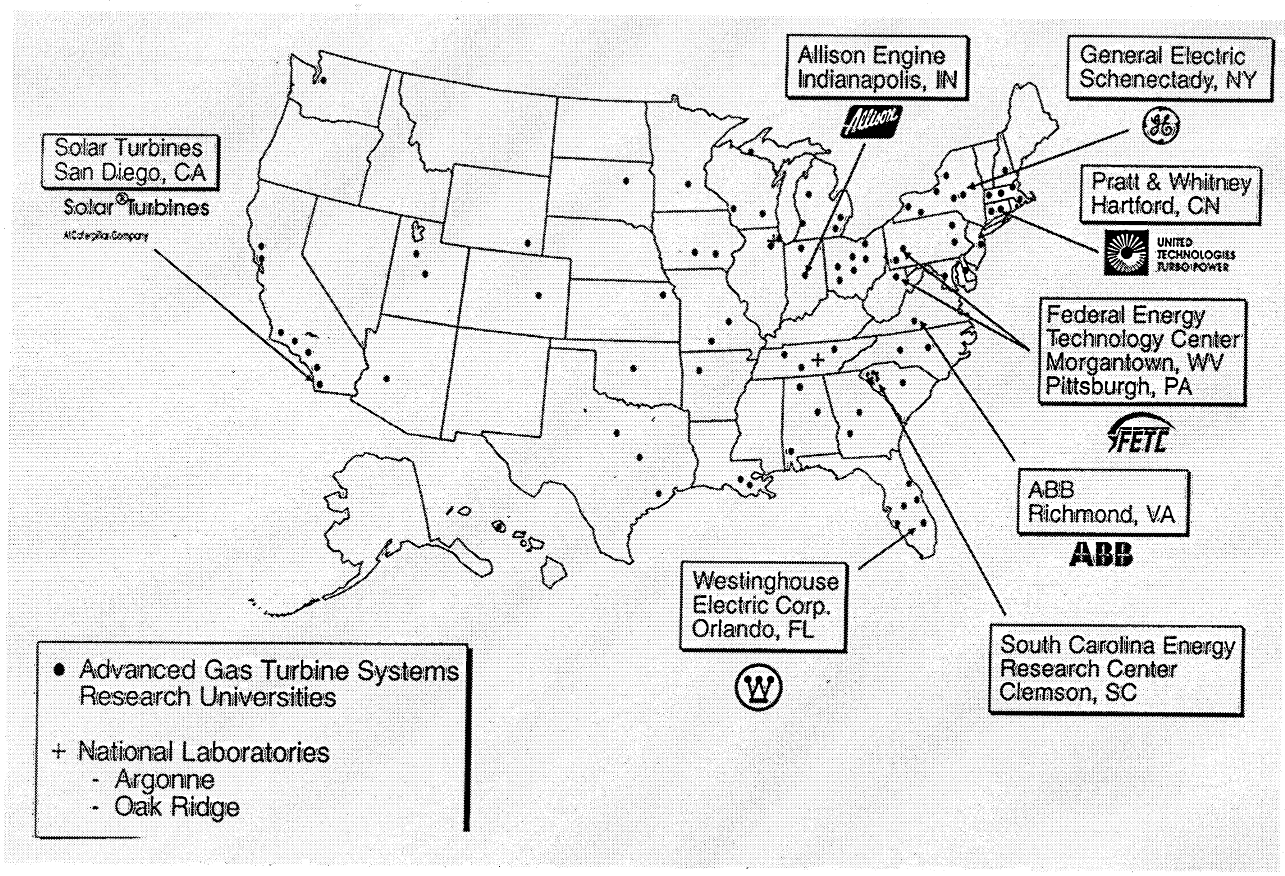
The Advanced Turbine System Program Participants

A Consortium of Universities, National Laboratories, U.S. Government, and Private Industry in 37 U.S. States



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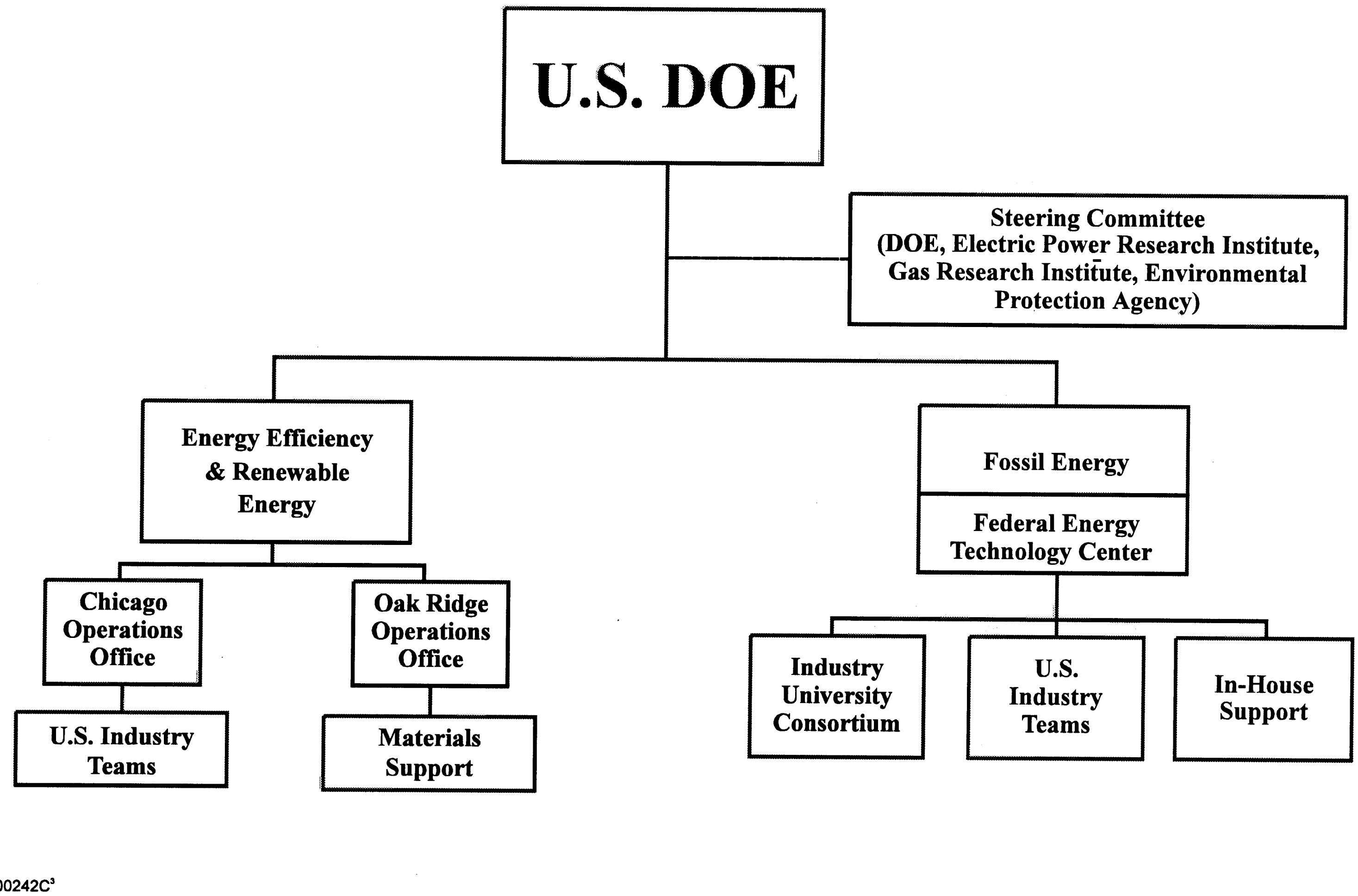
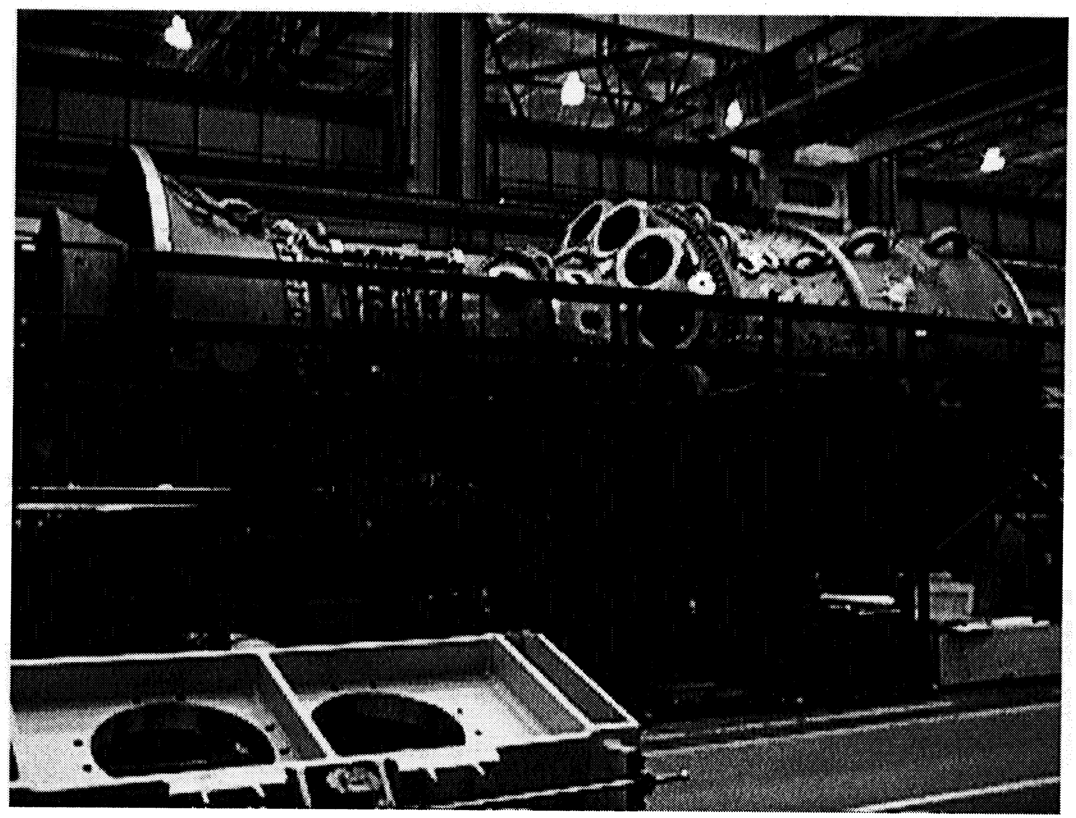
Management Structure for the ATS Program



General Electric Company

- Completed full scale testing of 9H(50Hz)ATS at Greenville SC
- Complete 7H(60Hz) ATS in FY 2000-2001 at Greenville SC
- Conduct pre-commercial demonstration of 7H ATS in FY 2001-2002



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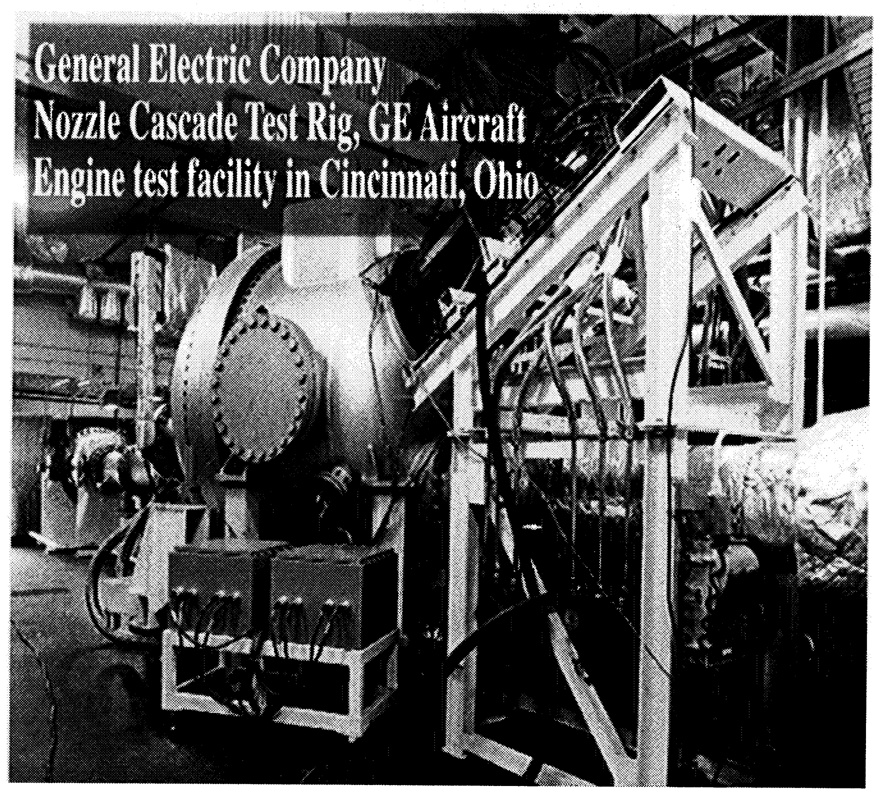
General Electric Company

Validation and Testing Program

- Full pressure combustion system at GE High Pressure Test Facility, Ohio
- Sub-scale compressor testing- GE Aircraft-, Lynn MA
- Steam cooled nozzle at GE High Pressure Test Facility, Ohio



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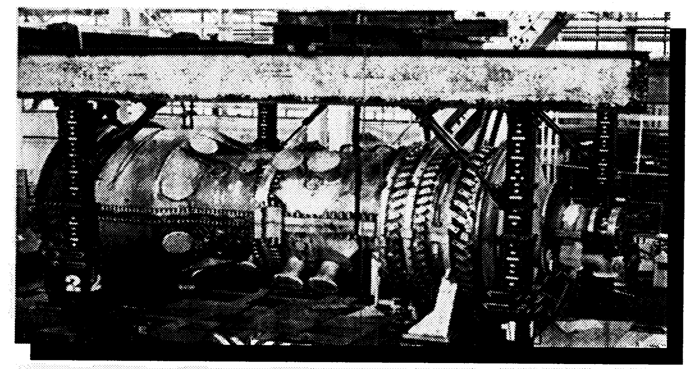
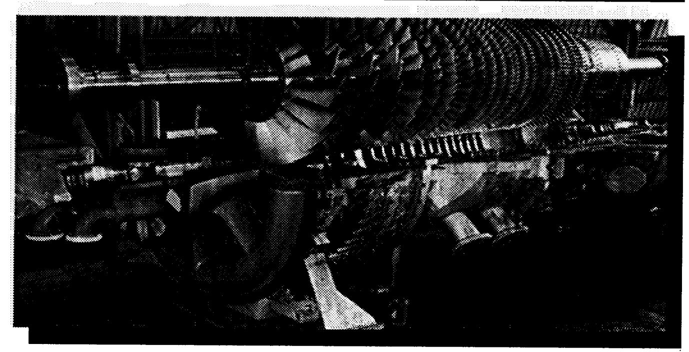
Siemens-Westinghouse Power Corporation

Turbine System Development and Testing

- Continue field testing of catalytic combustion and steam cooled systems on 501G
- Develop steam cooled vanes and test on 501GS power plant in FY 2001
- Manufacture 501 ATS and ship to customer site in FY 2002)
- Conduct pre-commercial demonstration on 501ATS in FY 2002





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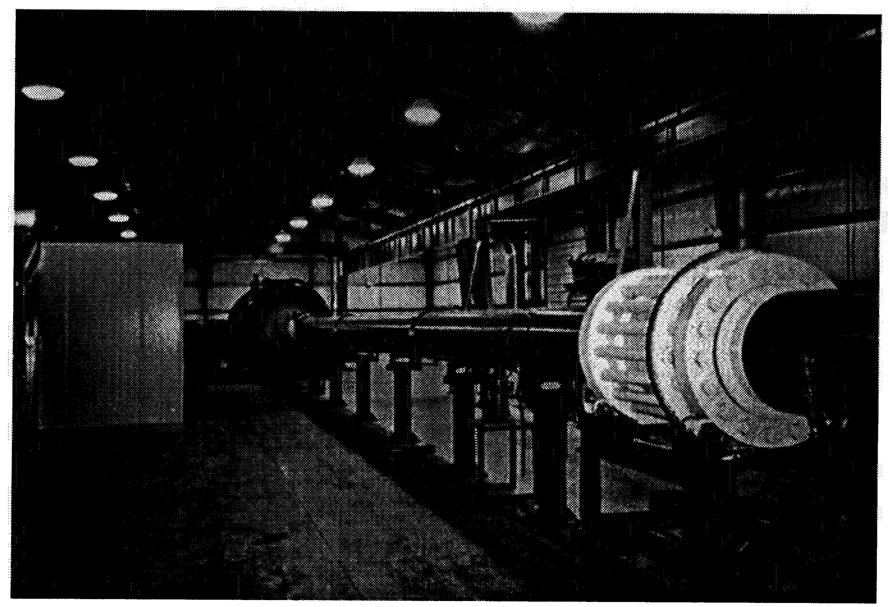
Siemens-Westinghouse Power Corporation

Validation and Testing Program

- Ohio State University Aerodynamic development testing on 1/3 scale model rig
- Catalytic combustion field testing on existing turbine
- Full scale steam cooled vane testing at Arnold Airforce Base



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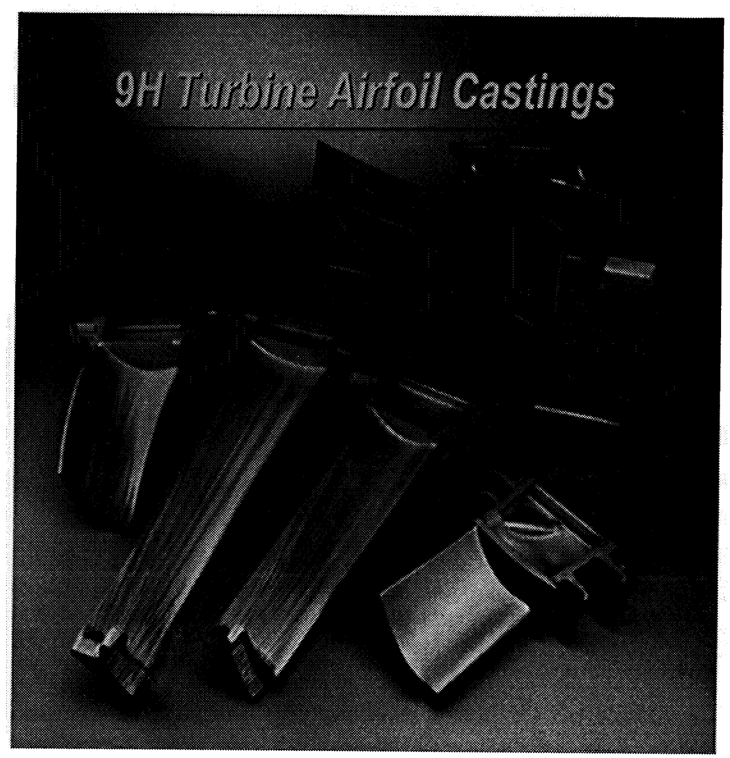
Manufacturing Materials

Oak Ridge National Laboratory-FETC

Projects with: GE-PCC Airfoils, Siemens-Westinghouse, Howmet-GE-Solar

- Utility scale single crystal blades-reduced sulfur/no grain defects
- New core materials and processes, NDE
- Grain orientation control
- New projects - cost reduction, increased yield rates



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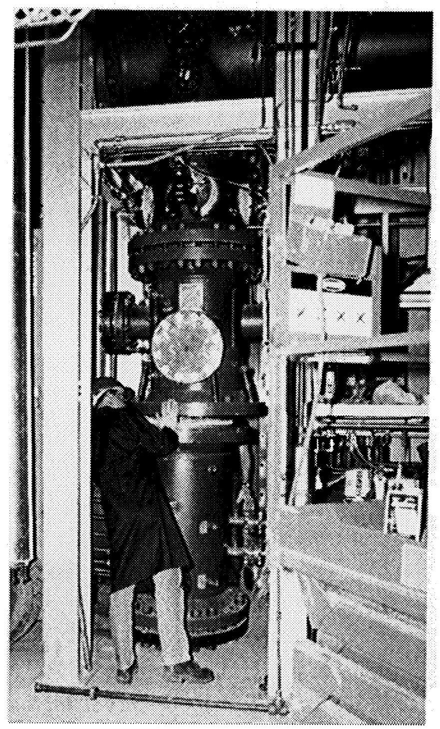
Federal Energy Technology Center
Combustion Division

Low Emissions Combustion Test Rig -

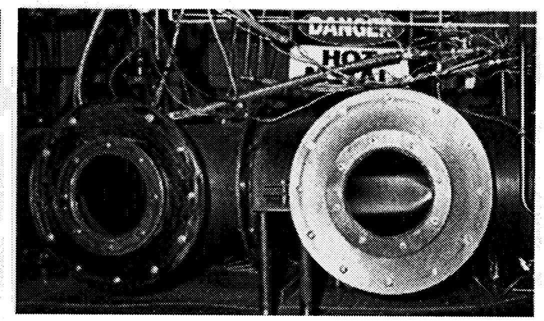
- Porous radiant burner
- Humidified cycle combustion
- Dynamic Gas Turbine Combustor
- Tested "active" and "passive" control techniques
- Emerging work aimed at reducing turbine fuel sensitivity, fuel premixing problems and flashback.

Atmospheric Pressure Test Rig

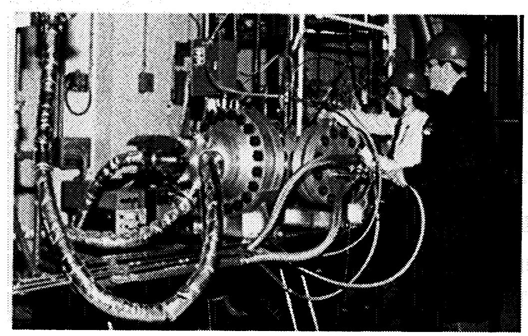
- Currently modifying for fuel flexibility studies



Low Emission Combustion Test Rig



Atmospheric Pressure Test Rig



Dynamic Gas Turbine Combustor

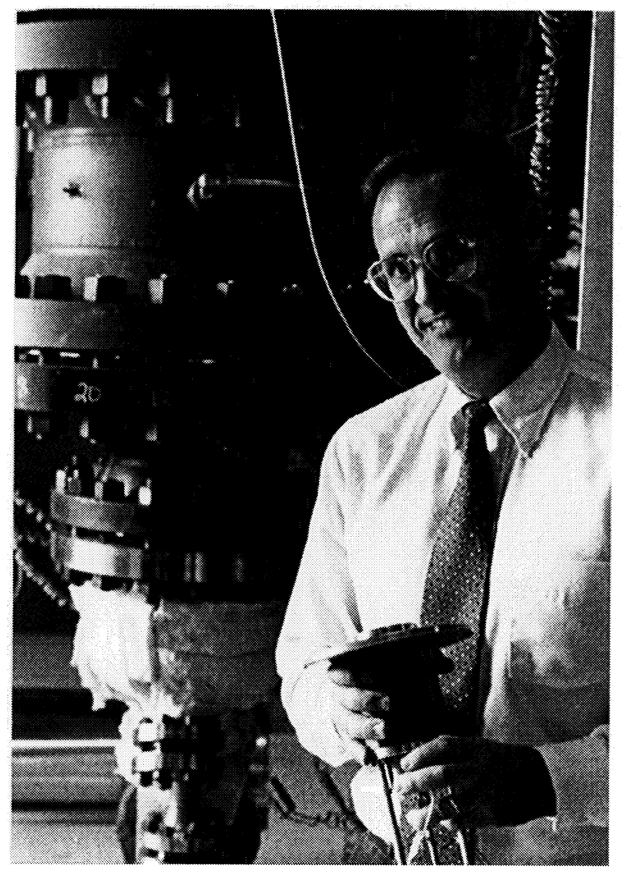
U.S. Department of Energy - ORNL & FETC

M990136P

M98000261C

FETC - Low Emissions Combustion Testing

- Alzeta - outward fired, surface stabilized burner at 12 atm pressure
- United Technologies Research Center - low Nox/CO levels at high steam loadings(20%)



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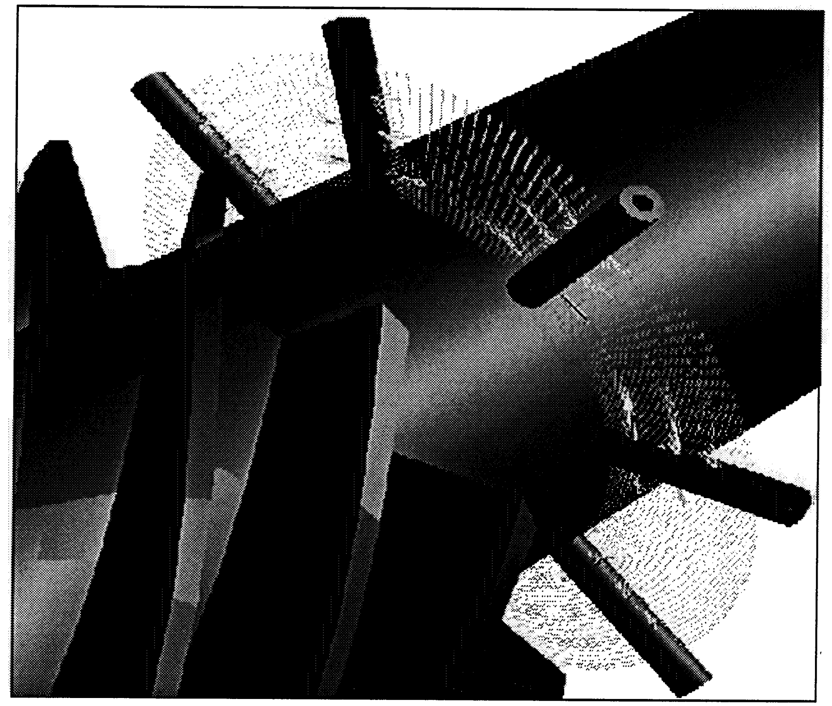
FETC - Combustion Dynamics Control

- Parker-Hannifan nozzle for dual fuel/ low emissions
- Effects of swirl vanes on stability-CFD and experimental validation
- Engine scale control of instabilities



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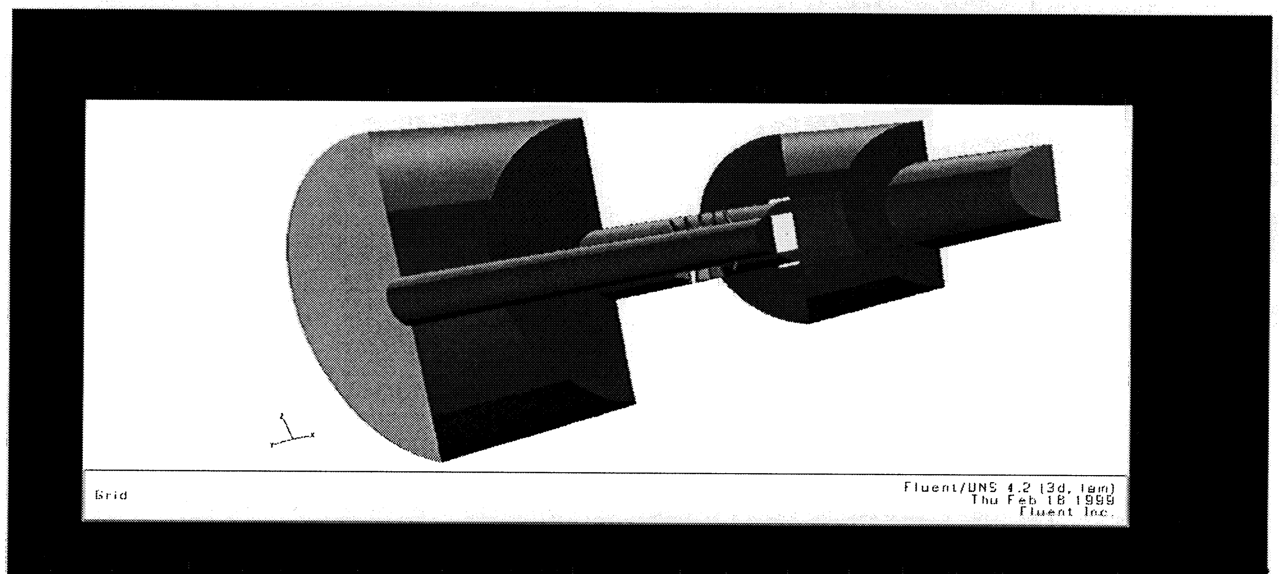
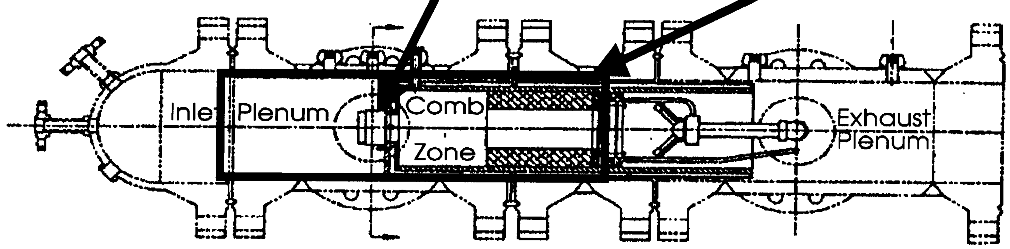
Fluent Model of FETC Gas Turbine Nozzle



Simulate this region



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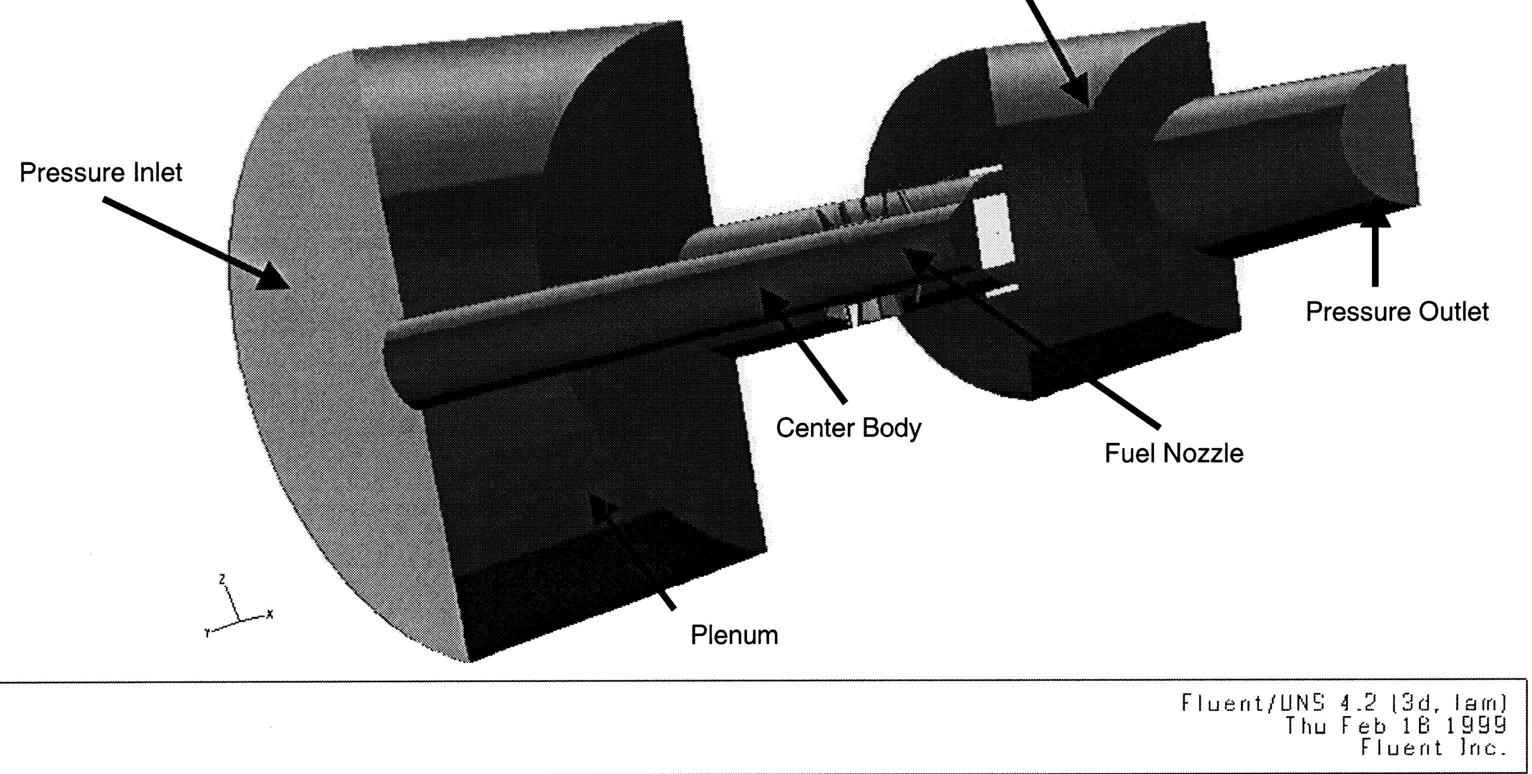
Computational Domain View From Plenum End



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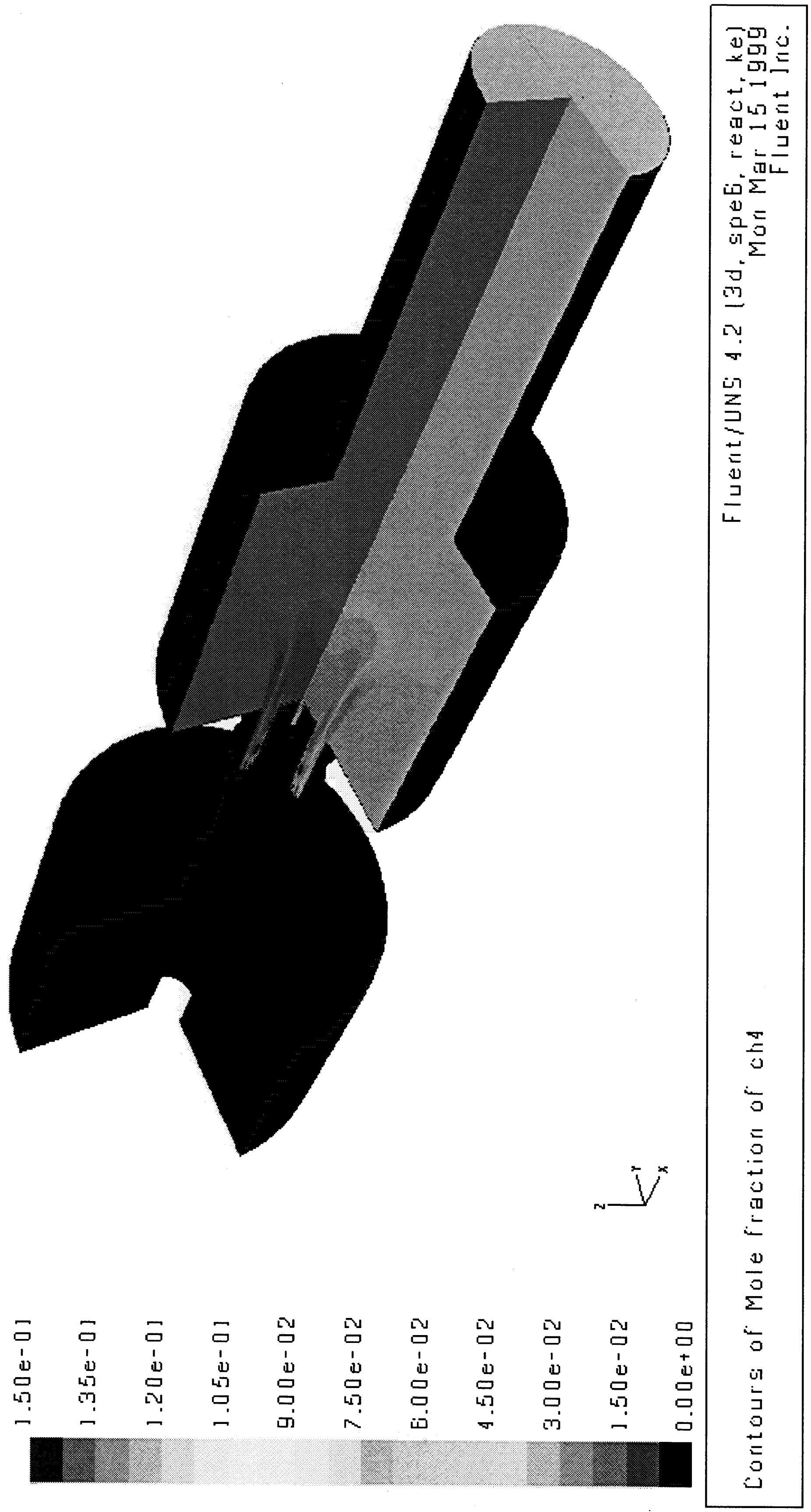

1.50e-01
1.35e-01
1.20e-01
1.05e-01
9.00e-02
7.50e-02
6.00e-02
4.50e-02
3.00e-02
1.50e-02
0.00e+00
Contours of Mole fraction of ch4
Fluent/UNS 4.2 (3d, spe6, react, ke)
Mon Mar 15 1999
Fluent Inc.

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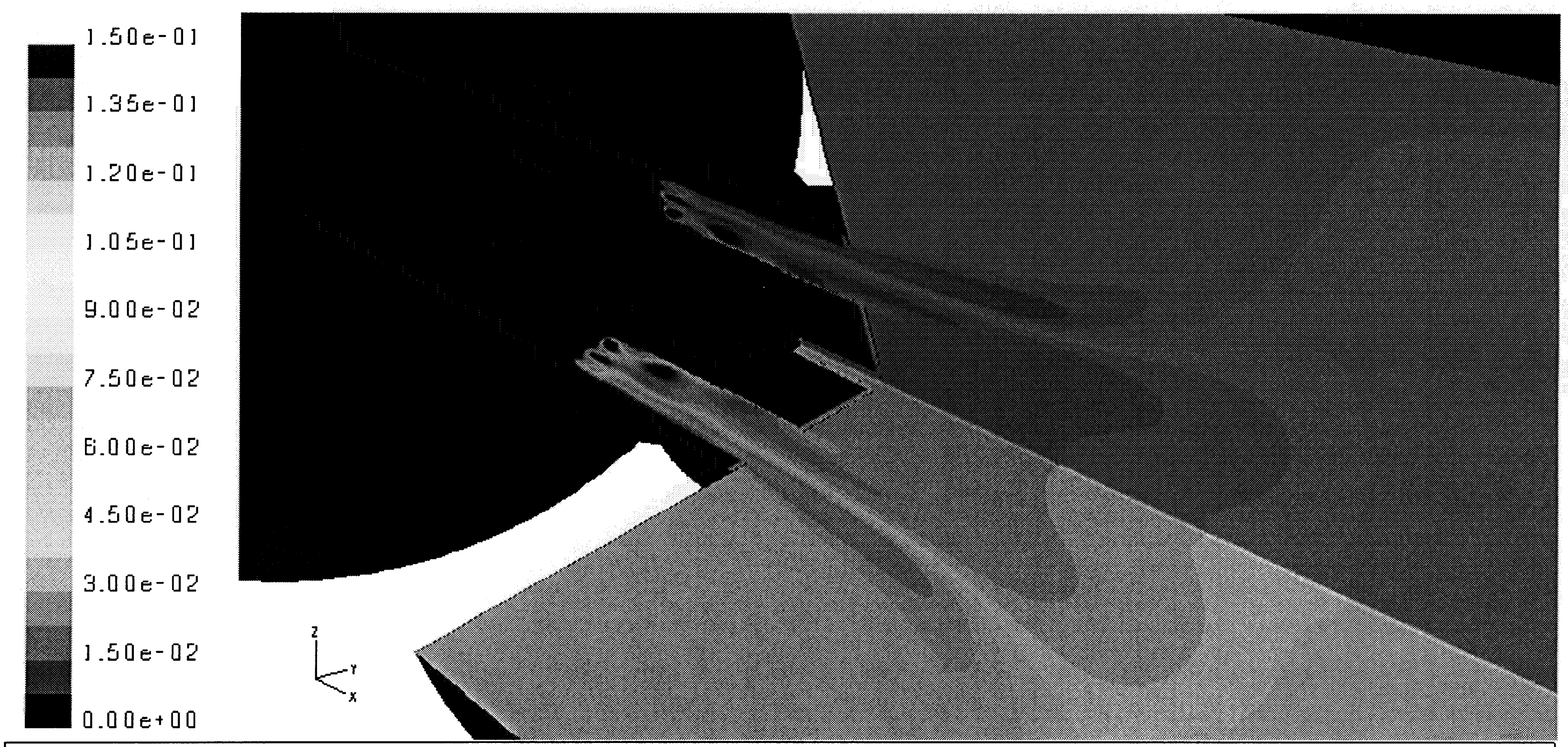

Contours of Mole fraction of ch4

Fluent/UNS 4.2 (3d, spe6, react, ke)
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Fluent Inc.

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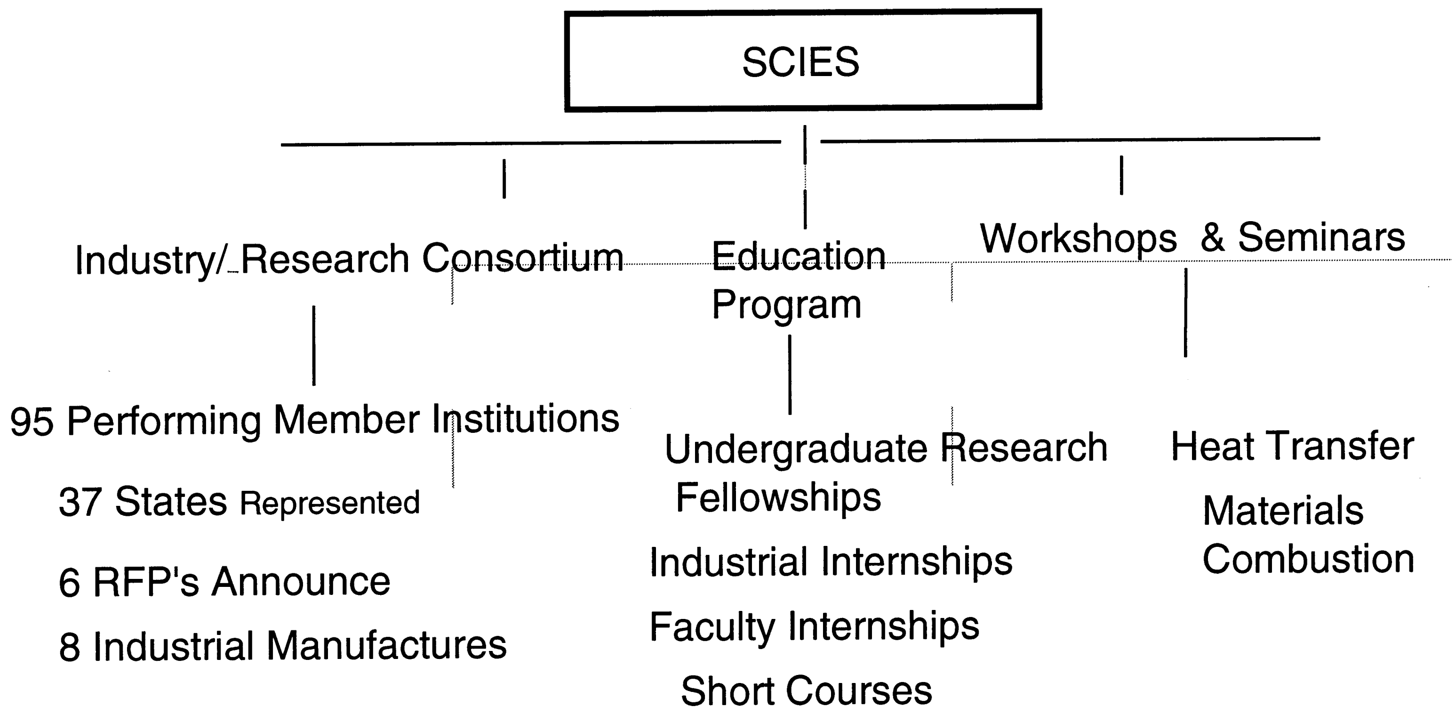
Industry/University Consortium



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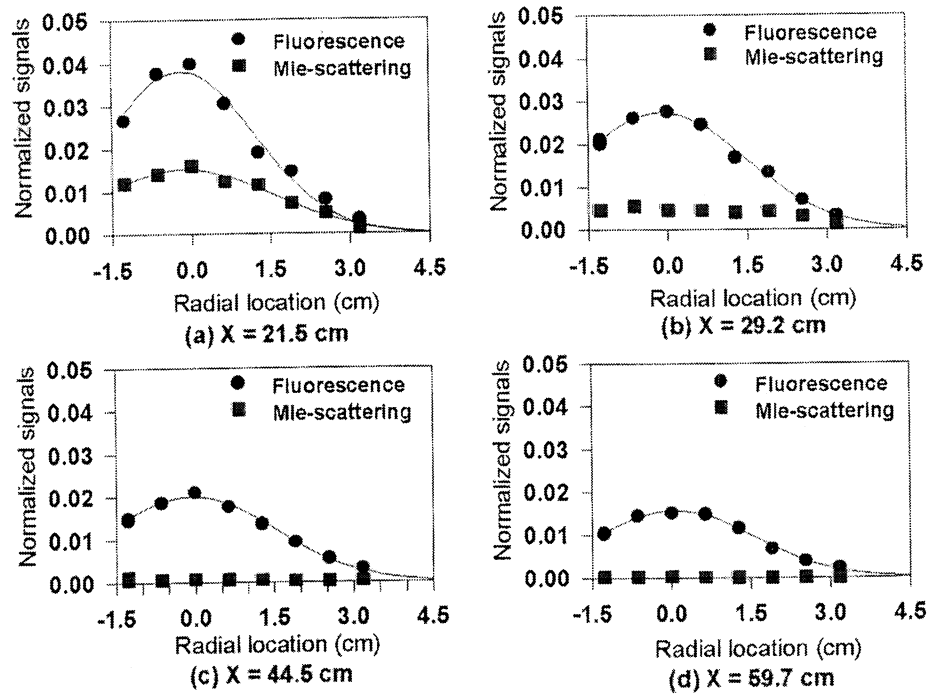
Combustion

Industry/University Consortium

- New equivalence ratio sensors(Penn State, Berkely, Georgia)
- Infrared sensor for temperature measurements(Purdue)
- Efficient chemistry algorithm(Cornell)
- 5 workshops



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Next Generation Turbine and Engine Systems - DOE Office of Fossil Energy-FETC

- ***Fuel Cell Hybrid Systems(engines and turbines)***
  - High efficiency, low emissions
  - Distributed generation
  - Long Term Vision 21 systems
- ***Advanced Mid-size turbines***
  - Flexibility
  - Efficiency improvements for existing fleet of power plants(coal, gas, oil)

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Next Generation Turbine and Engine Systems - DOE Office of Fossil Energy-FETC

- ***Vision 21-High Efficiency Engines and Turbines***
  - Advanced turbine cycles
  - Ultra high temperature, pressure
  - Reheat and/or inter-cooling
- ***Advanced Reciprocating Engine Systems***
  - Distributed Power
  - Ultra high efficiency
  - Lowest emissions technology
  - Natural Gas fueled

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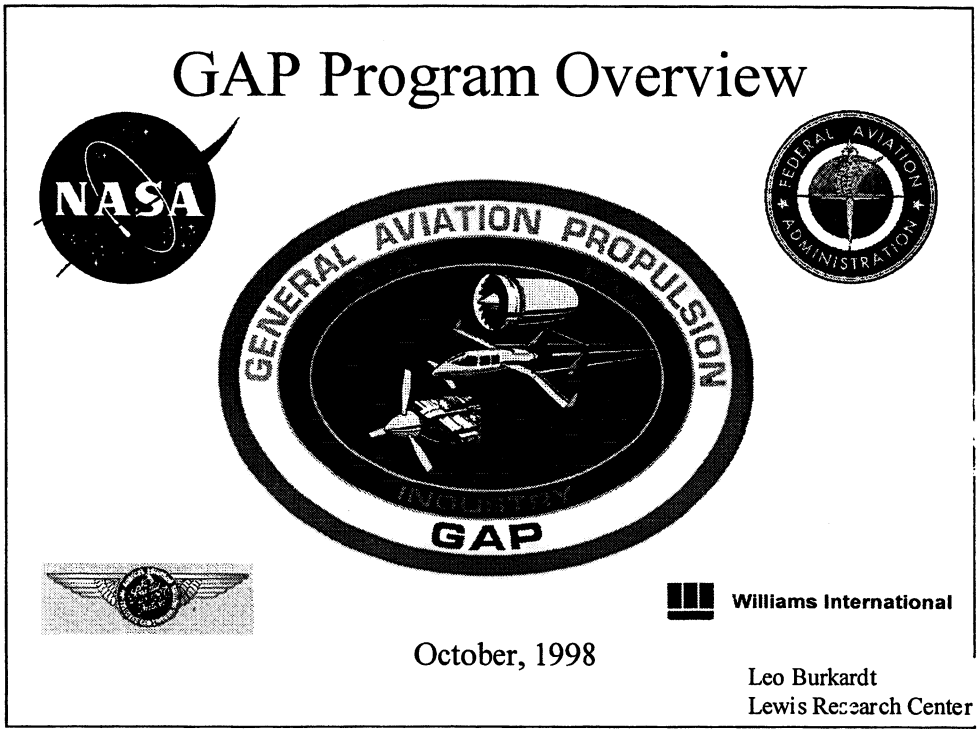
Next Generation Systems Will...

- Build on success of ATS program
- Result in significant air emissions reductions
- Accelerate the overall efficiency increase of the existing and new power generation fleets in the U.S.(coal,oil,gas)
- Develop an effective pathway to Vision 21 systems

M990136P

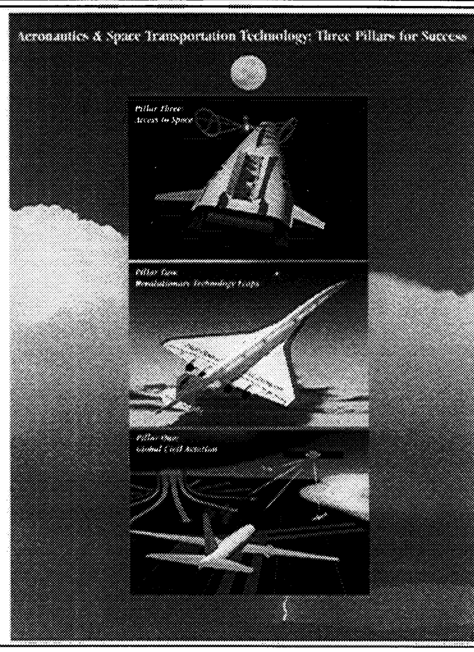
GAP PROGRAM OVERVIEW

Leo Burkardt
NASA Glenn Research Center
Cleveland, Ohio



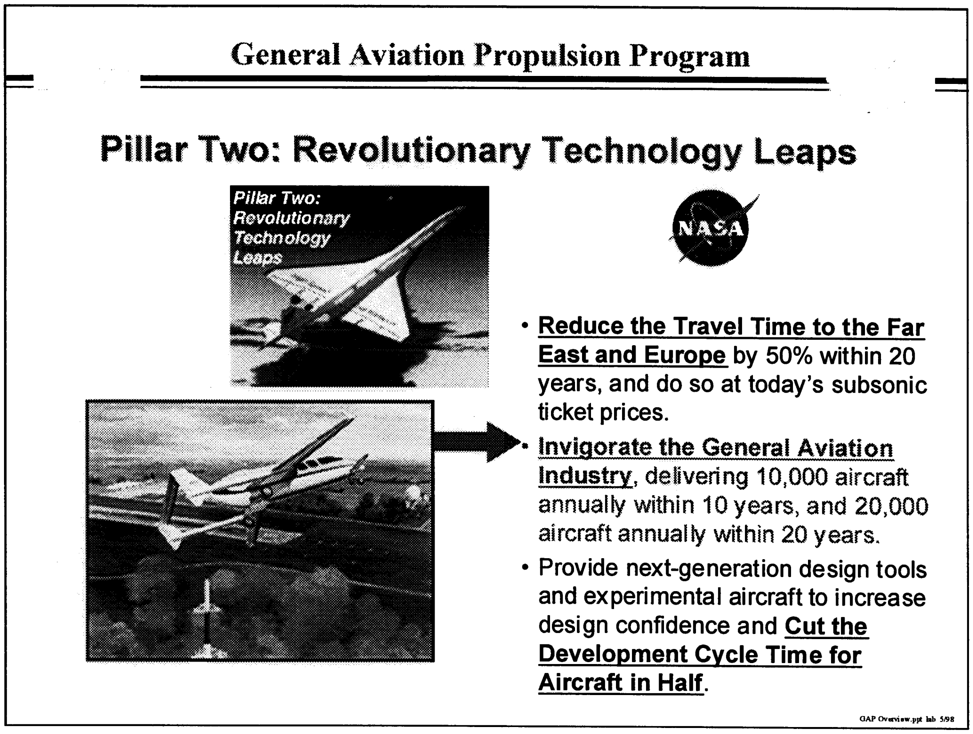
NASA's General Aviation Propulsion (GAP) program is a cooperative program between government and industry.

General Aviation Propulsion Program



GAP Overview.ppt lab 5/98

NASA's strategic direction is described by the "Three Pillars" and their Objectives as set forth by NASA Administrator Daniel S. Goldin. NASA's Three Pillars are: 1) Global Civil Aviation, 2) Revolutionary Technology Leaps, 3) Access To Space.



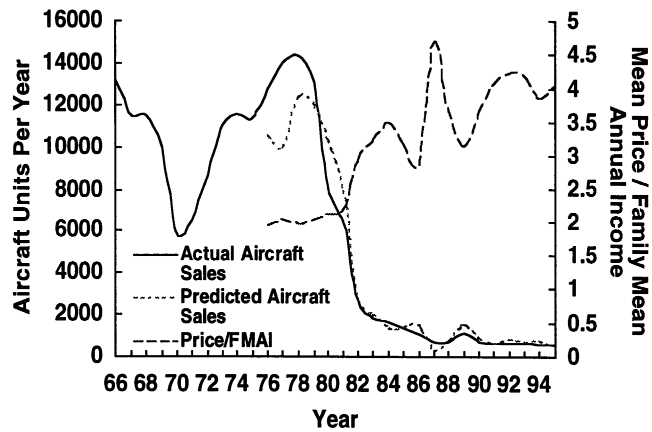
General aviation has fallen far behind in technology and affordability, therefore NASA's has included general aviation technology development under Pillar Two, Revolutionary Technology Leaps. The enabling technology Objective is: Invigorate the general aviation industry, delivering 10,000 aircraft annually within 10 years, and 20,000 aircraft annually within 20 years.

Putting NASA's goal in perspective, it means developing technologies that will once more enable general aviation manufacturers to produce aircraft that are attractive and affordable to the public. Though the production numbers stated in the Three Pillars Objective may seem fantastic compared to today's production levels, they really are stating nothint more than we would like to get back to the production level which general aviation once enjoyed before the "big crash" of the 80s. Before 1980 the sales trend for general aviation aircraft generally followed the gross national product.

With the average age of the current general aviation light aircraft fleet being approximately 30 years and the basic technology level incorporated into those aircraft being much older than that, the market is ripe for rejuvenation.

General Aviation Propulsion Program

Predicted vs Actual Piston Aircraft Sales



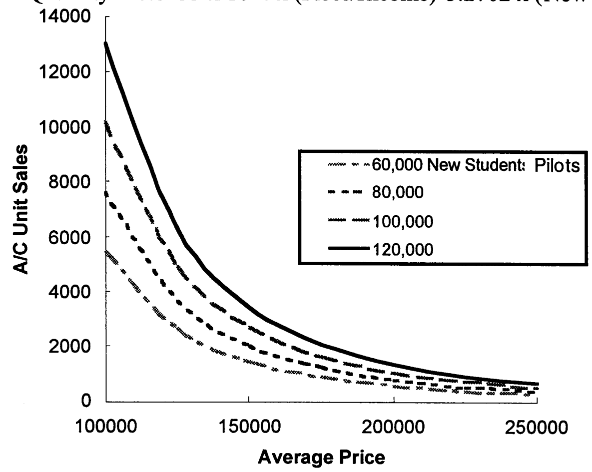
This chart shows the history of the general aviation market for the last 30 years. The market was able to recover from the first down turn in the late 60s but it essentially crashed after the down turn in the late 70s. As can be seen from the plot of aircraft price vs. family income, it was at the same time as the second down turn that aircraft price began to escalate dramatically. The obvious conclusion is that the rise in aircraft price played a big part in preventing a recovery in the market in the 80s and has kept the market at its very depressed levels ever since. The red line is a plot of an equation which was developed to represent the market history since the mid 70s. This equation is based on aircraft price and the number of pilots available to buy aircraft. It can also be used as a market demand model to assess the impact of GAP engine technologies on the market place based solely on the technologies effect on engine price. Engine performance and ease of use are not factored in to the equation, so predictions based on this equation should be conservative, that is, predict a smaller impact on aircraft sales than would be expected if performance and ease of use were also considered.

General Aviation Propulsion Program

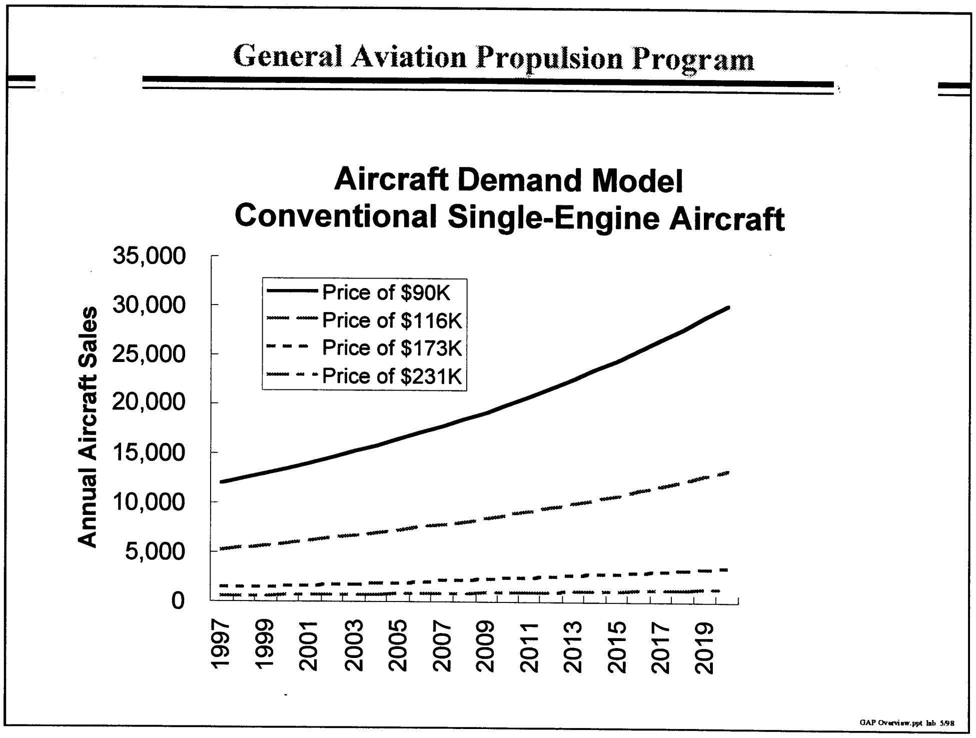
Aircraft Demand Model

(Evaluated at $55,000 Mean Income)

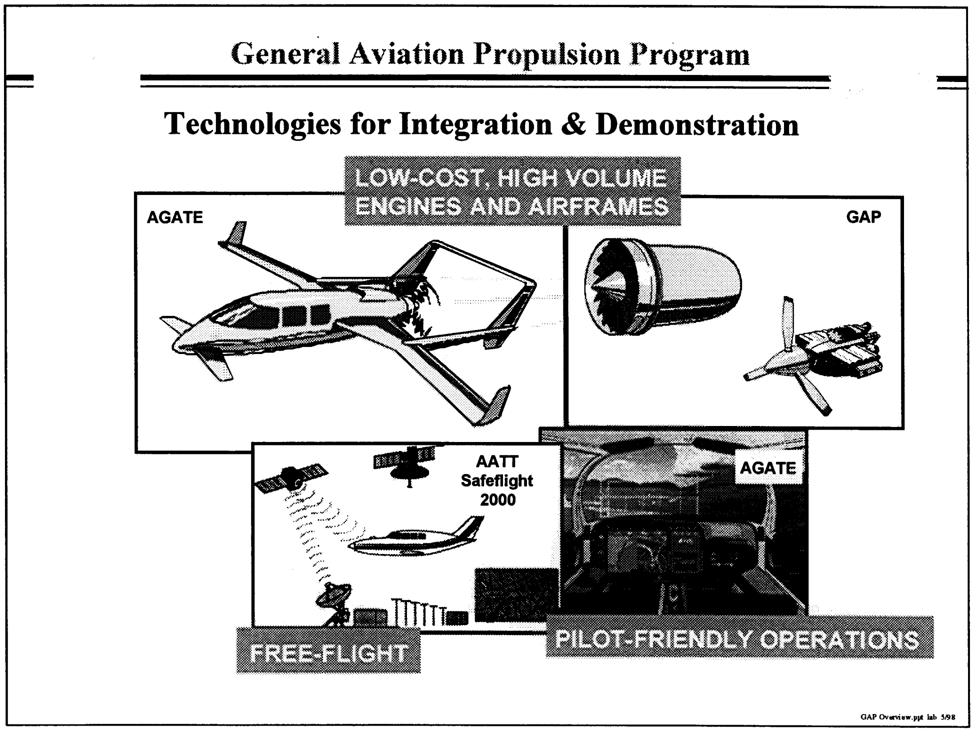
Quantity = 0.6433 x 10-4 x (Price/Income)-3.2702 x (New Pilots)1.9503



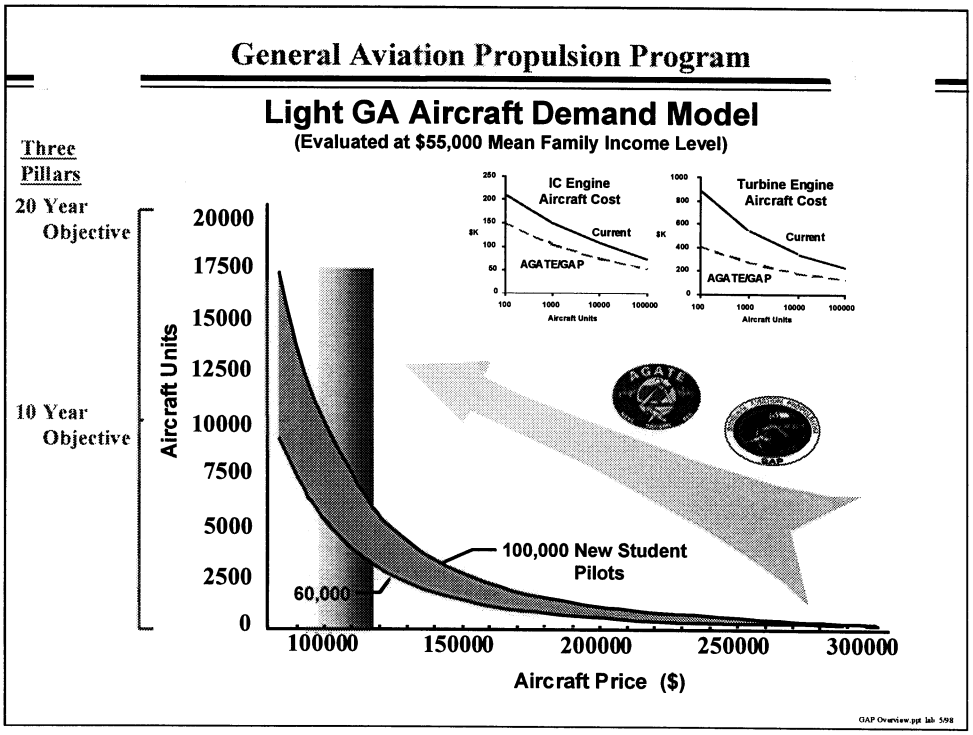
Using the market demand model developed from previous general aviation market history the effect of aircraft price on sales of aircraft can be predicted. The four lines represent different assumptions for the number of new pilots who would be potential buyers for an aircraft.



Assuming we start out with 100,000 new pilots in the first year with additional new pilots coming in to the market every year after that, this chart shows how many aircraft of various price levels might be sold on a yearly basis. Replacement of current aircraft is not included in this scenario, it assumes that only new pilots who don't yet own an aircraft would be buying the new aircraft. The number of new pilots each year is based on the goals of current general aviation industry pilot recruitment promotional efforts.



NASA, the FAA and the general aviation industry are all cooperating in trying to bring about the resurgence of general aviation. NASA has programs aimed at meeting the technology needs of the total general aviation market place and infrastructure. The two programs specifically aimed at general aviation are the Advanced General Aviation Transport Experiments (AGATE) program and the General Aviation Propulsion (GAP) program. AGATE is developing airframe and avionics technologies. GAP is concentrating on new engine development. Other NASA programs, while not specifically aimed at general aviation, have components which address the needs of general aviation. One such program is Advance Air Transportation Technology (AATT). This program is developing technologies for the air traffic control infrastructure which will increase safety, provide for greater numbers of aircraft and allow more aircraft freedom in routing and flight paths. General aviation is an important part of this air traffic picture.



Using engine price goals of the GAP program along with aircraft and avionics price goals of the AGATE program, which should enable the industry to sell a single engine 4 place aircraft for about $100,000, it looks as though the Three Pillars Objective of reaching a production rate of 10,000 aircraft per year in 10 years is within reach.

General Aviation Propulsion Program

General Aviation Propulsion Program:

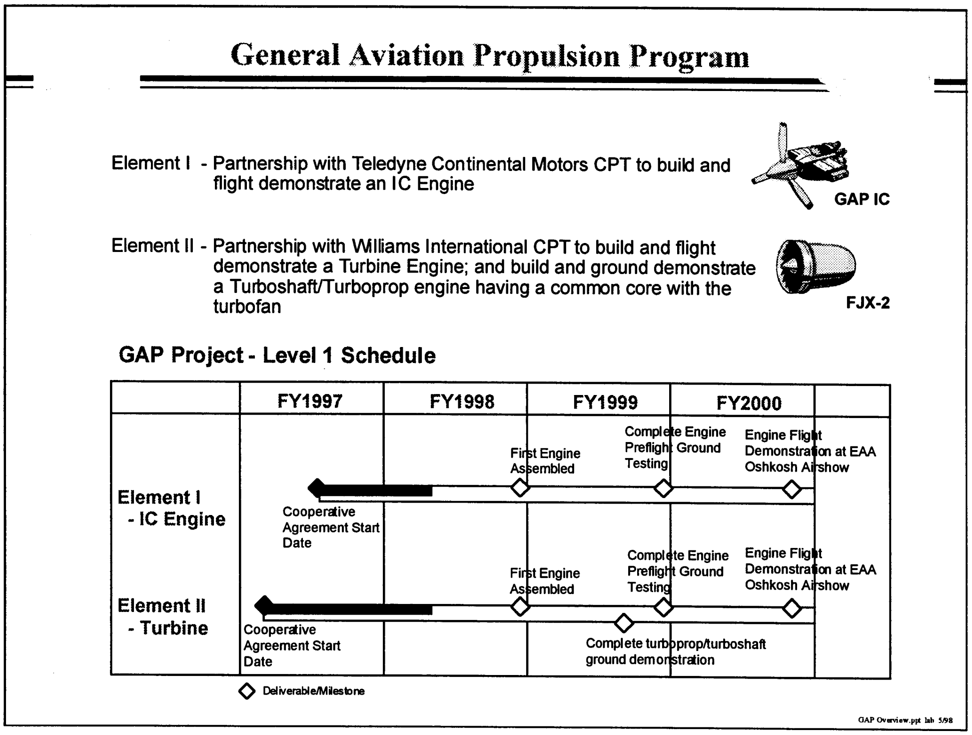
Goal: Develop and flight-demonstrate revolutionary propulsion systems for general aviation aircraft to support revitalization of the U.S. General Aviation Light Aircraft Industry

Objectives: Through a NASA/Industry/FAA Partnership -

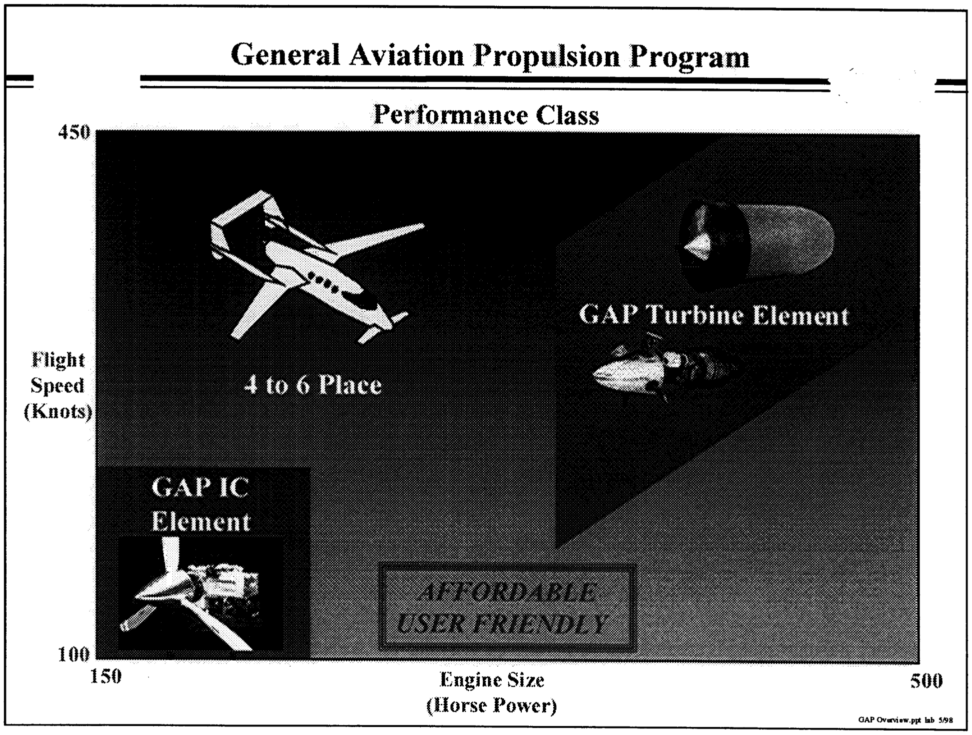
- Develop technologies and processes that will result in low-cost, environmentally compliant, revolutionary propulsion systems for light general aviation aircraft
- Flight-demonstrate proof-of-concept

GAP Overview.ppt lab 5/98

The General Aviation Propulsion program was established to address the technology needs of the general aviation engine industry. The specific goal of GAP is to develop and flight demonstrate revolutionary propulsion systems for general aviation aircraft to support revitalization of the U.S. General Aviation Light Aircraft Industry. This will be done in partnership with the FAA by developing technologies and processes that will result in low-cost, environmentally compliant, revolutionary propulsion systems for light general aviation aircraft. The major milestone of the program is to flight demonstrate fully manufacturable, certifiable propulsion systems in the year 2000 which meet or exceed the cost and operability requirements of the program.



The GAP program is a four year program, begun in 1997, for which NASA has provided $55 million. Industry is making an equal investment in the program. GAP is divided into two Elements, the Intermittent Combustion (IC) Element and the Turbine Element. Each Element is implemented through a Cooperative Agreement with an industry led team. Each team will flight demonstrate its engine concept by the year 2000. The engine manufacturer on each team has committed to putting a new engine on the market, based on these engine concept demonstrators, within a couple of years after the completion of the GAP program.



The engine demonstrators being developed in GAP will cover both entry level aircraft and high performance aircraft. Commercial derivatives of these engines will be developed to cover the full spectrum of general aviation light aircraft applications.

General Aviation Propulsion Program

Engine Performance Goals

	IC	Turbine
Cost Reduction	50%	10^{-1}
Fuel	JP	
Ergonomic	Similar to Automotive Comfort, Ease of Use	
Maintenance Cost Reduction	50%	10^{-1}
Specific Fuel Consumption Reduction	25%	
Environmental Compliance		
- Emissions		
-- gaseous emissions reduction	Meet expected standards for year 2000+	Meet expected standards for year 2000+
-- particulate visibility	Meet expected standards for year 2000+	Meet expected standards for year 2000+
- Noise	Meet expected standards for year 2000+	Meet expected standards for year 2000+

GAP Overview.ppt lab 5/98

The design goals which have been set for each Element are as follows:

IC Element

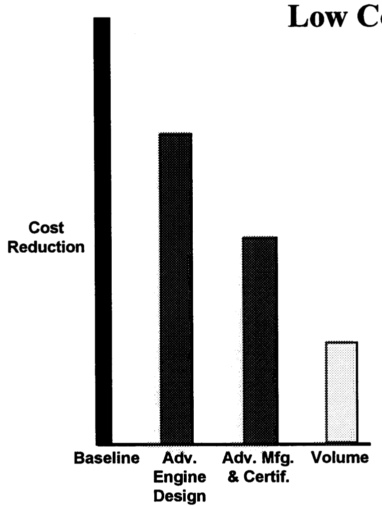
Reduce acquisition and maintenance costs by 50% compared to current engines. Avoid the use of leaded gasoline or any other environmentally dangerous fuel; use jet fuel if possible. Achieve propulsion related comfort and ease of use levels similar to those in the automotive world. Meet or exceed expected environmental regulations.

Turbine Element

The turbine engine already has the types of characteristics needed except for cost, so the major goal here is to reduce the acquisition and maintenance costs of small turbine engines by an order of magnitude while maintaining good performance levels. As with the IC Element the engine must meet or exceed expected environmental regulations.

General Aviation Propulsion Program

Low Cost Engine Strategy



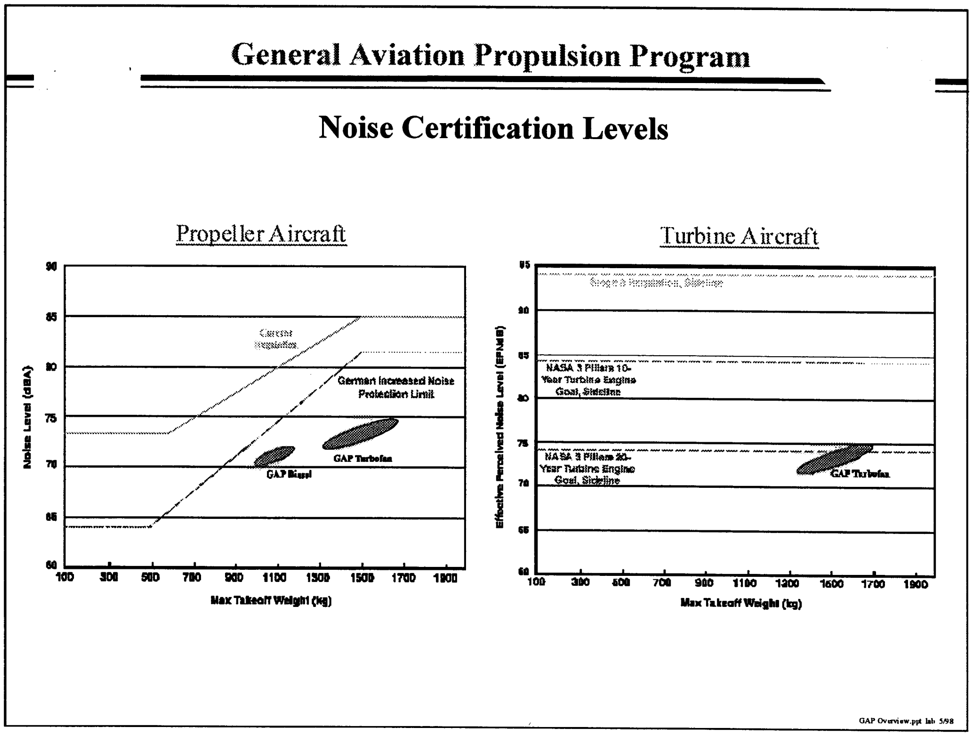
Advanced Engine (Keep it Simple):
- Common Core Approach
- Design Simplicity – Min. Components
- Concurrent Engineering – Simplified Assembly
- Avoid Exotic Materials
- Electronic Fuel Control
- Fast Prototyping

Advanced Manufacturing Methods:
- Near Net Forming
  - Precision Casting
  - Precision Stamping
  - Precision Extruding
  - Other Advanced Processes
- High Speed Machining
- Advanced Joining Methods
  - Laser Welding
  - HIP Diffusion Bonding
  - Inertia Welding
  - Other Advanced Methods

Certification
- **Early FAA Involvement**

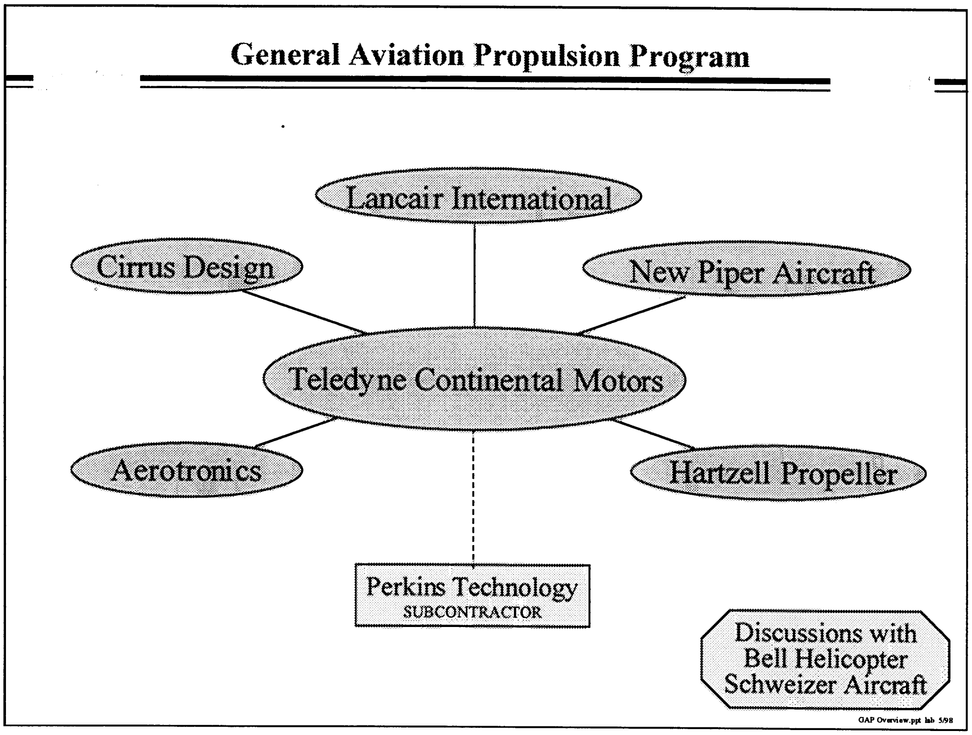
Production
- Volume

The approach to achieving low cost is three pronged. First, design the engine to be as simple and with as few parts as possible. Second, design the engine with ease of manufacture and assembly as a primary objective. Design for high volume manufacturing methods. Third, build a large market base by making the engines as versatile as possible to cover the widest number of applications. Develop non-traditional markets such as marine applications.



Aircraft powered by commercial derivatives of the GAP engines will be the quietest aircraft in the air, both for those on the ground and for the passengers. They will meet future noise regulations.

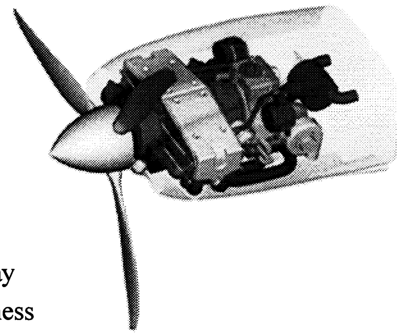
IC Engine Element



The NASA industry partner for the IC Element is a team headed by Teledyne Continental Motors (TCM). The team consists of three airframers, Cirrus Design, Lancair International and New Piper Aircraft, to ensure that the new engine and propulsion system will fit the needs of the airframe companies for new products and to allow integrated engine/aircraft system design at the earliest stages of development. Aerotronics is developing engine controls and displays. Hartzell Propeller is developing quiet propeller designs. Perkins Technology is subcontracted to TCM for detailed engine design and analysis. There have also been discussions with helicopter manufactures to ensure that their requirements are met.

General Aviation Propulsion Program

Teledyne Continental Motors CSD 283



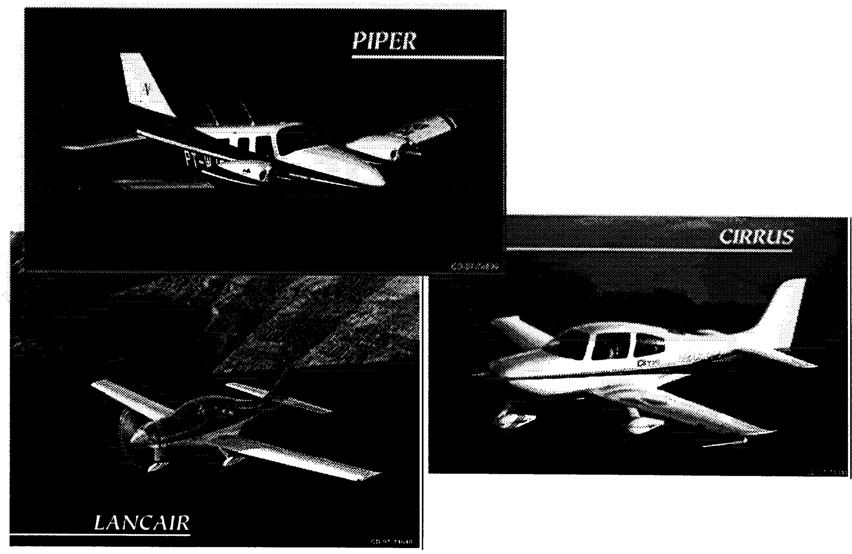
- Compression Ignition Engine
- 2 Stroke, Direct Injection
- Liquid Cooled
- 200-bhp @ 2200-rpm
- Jet Fuel
- Single Lever Power Control
- Electronic Diagnostics and Display
- Low Noise, Vibration and Harshness
- Meets Expected Future Emissions Requirements
- 1/2 Cost Current Engines

GAP Overview.ppt lab 5/98

The engine being developed under the IC Element is a horizontally opposed, two stroke, compression ignition (diesel) engine which will run on jet fuel. Jet fuel is much more available world wide than gasoline and is much cheaper than gasoline in some areas. The demonstrator engine will be a 4 cylinder 200 horse power engine. It is designed to enable easy growth to 6 and 8 cylinder versions. It is a direct drive engine with a propeller shaft output speed of 2200 rpm. The reduction in output speed from the current 2700 rpm will facilitate a major reduction in propeller noise. One power lever will control the propulsion system including engine power and propeller pitch, there is no mixture control on a diesel engine. The engine will have a very low parts count and be designed for automated production methods to achieve a 50% reduction in cost.

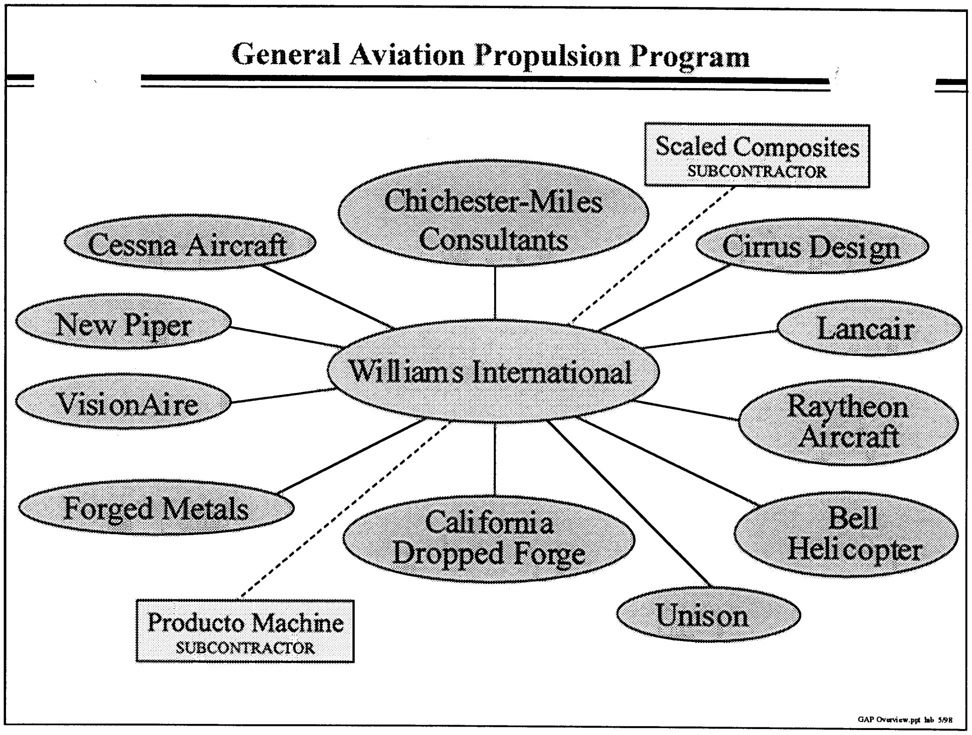
General Aviation Propulsion Program

GAP IC Engine Demonstrator Aircraft



The GAP IC engine will be flight demonstrated at on three aircraft, the Cirrus SR20, the Lancair Columbia and the Piper Seneca IV.

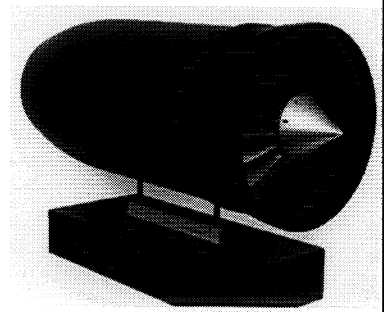
Turbine Engine Element



The NASA industry partner for the Turbine Element is a team headed by Williams International (WI). The team consists of seven airframers, Cessna Aircraft, Chichester-Miles Consultants, Cirrus Design, Lancair, New Piper Aircraft, Raytheon Aircraft and VisionAire, to ensure that the new engine and propulsion system will fit the needs of the airframe companies for new products and to allow integrated system design at the earliest stages of development. Unison is developing the engine ignition system. California Drop Forge and Forged Metals are working on low cost forging techniques. Producto Machine is subcontracted to WI to develop very precise low cost machining capabilities for small engine components. High precision is needed to maintain good performance capabilities in small engines. Scaled Composites is subcontracted to WI for final design, manufacture and flight testing of the V-Jet II demonstrator aircraft. A totally new aircraft is needed to fully demonstrate the aircraft design and performance capabilities which this engine will enable.

General Aviation Propulsion Program

WILLIAMS INTERNATIONAL FJX-2

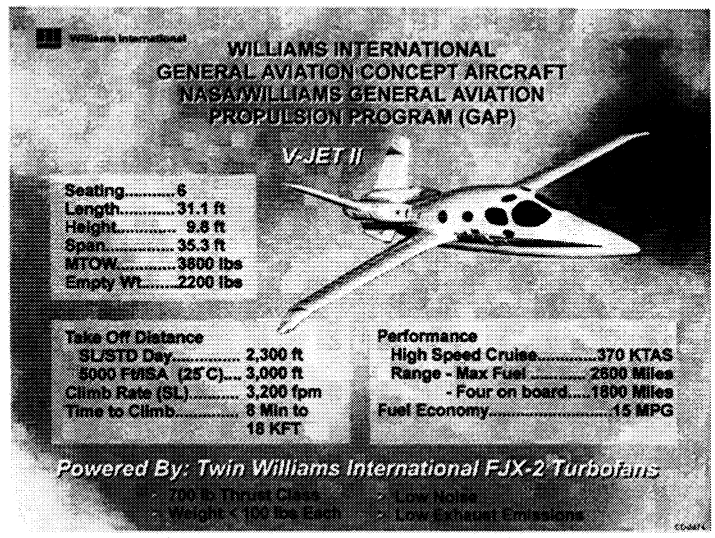


- Turbofan, Bypass Ratio of 4
- 700-lb Thrust Class with Growth Capability
- 14-inch Diameter by 41-inch Length
- Weighs less than 100 lbs.
- Jet Fuel
- Cost Competitive with Comparable Power Piston Engines of Today
- Single Lever Power Control
- "Take-off to Landing" Fuel Burn Less Than Comparable Piston Engine Power Airplane
- Meets Future Exhaust Emissions and Noise Requirements
- Common Core Design For Turboprop & Turboshaft Versions

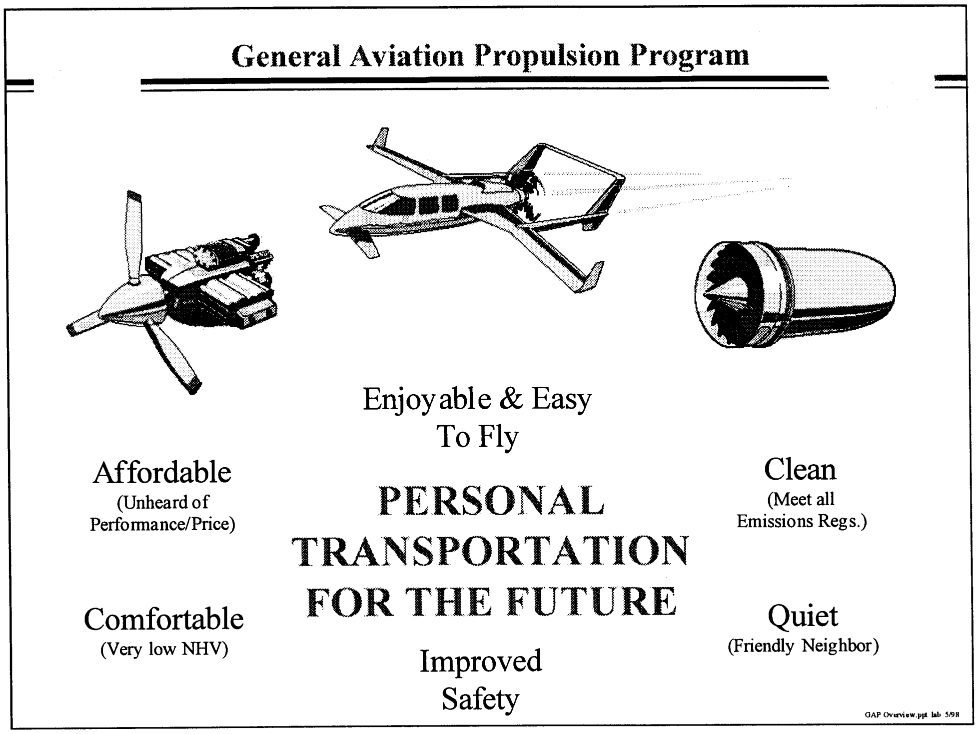
GAP Overview.ppt lsb 5/98

The FJX-2 turbine engine is a high bypass turbofan with a "common core" design which will enable turboprop and turboshaft versions of the engine to be designed and produced. The engine design point is a bypass ratio of about 4 with 700 lbs. sea level static thrust and a weight of less than 100 lbs., giving it an excellent thrust to weight ratio. At reasonable production levels the engine should be cost competitive with current piston engines. When the weight, performance and installation advantages this engine provides are taken advantage of in an integrated aircraft design, the aircraft fuel burn for a given mission will be comparable to a piston engine powered airplane.

General Aviation Propulsion Program



The V-Jet II was conceptually designed by Dr. Sam Williams with final design and manufacture performed by Scaled Composites. The aircraft was specifically built to demonstrate the revolutionary type of general aviation light aircraft that the FJX-2 engine will enable. An old axiom is “new engines enable new aircraft” and that is certainly born out by the FJX-2 and the V-Jet II. A twin engine demonstrator aircraft was selected for safety purposes since this is a totally new engine being flown for the first time in a totally new aircraft. As seen in the chart the aircraft has excellent performance and weight characteristics. Although there is no intention to manufacture the aircraft, the V-Jet II was designed to be fully produceable with low cost manufacturing techniques and viable as a certified production aircraft so that there would be no doubt as to the potential that the FJX-2 introduces in to the general aviation light aircraft market. The aircraft was demonstrated for the first time at the Experimental Aircraft Association’s Oshkosh’97 Fly-In Convention. The V-Jet II currently has FJX-1 interim engines installed which do not allow it to meet its full performance potential or fuel consumption goals, but do allow the aircraft to be checked throughout most of its flight envelope before the FJX-2 engine is ready.



Coming soon, with the completion of the GAP and AGATE programs, are light general aviation aircraft that are fun and easy to fly. They will be affordable, comfortable and allow general aviation to be a friendly neighbor. We will have the makings of a true personal transportation system which everyone can enjoy!

RECENT PROGRESS IN AIR/OIL SEALS RESEARCH AT ALLIEDSIGNAL

M. Rifat Ullah
AlliedSignal Aerospace
Phoenix, Arizona

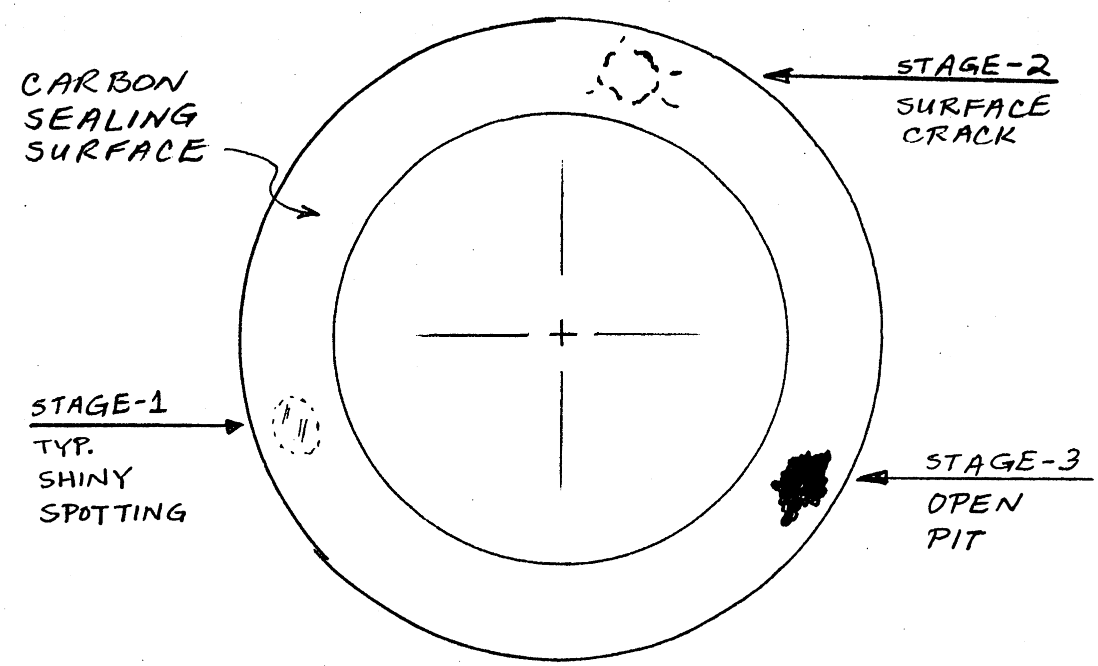
Carbon Seal Blister Prevention Research (1997-1998)

OUTLINE:

- Microstructure of Carbon-Graphite
- Modeling Current Blister Theories
- Blister Rig Development, for Repeatable Results
- Method Development: Blister Test & Damage Measurement
- "Ranking" Tests for Various Carbon-Graphites
- Measurement of Key Properties
- Correlating Blister Damage to Relevant Variables
- Results To-Date

Stages of Blistered Carbon

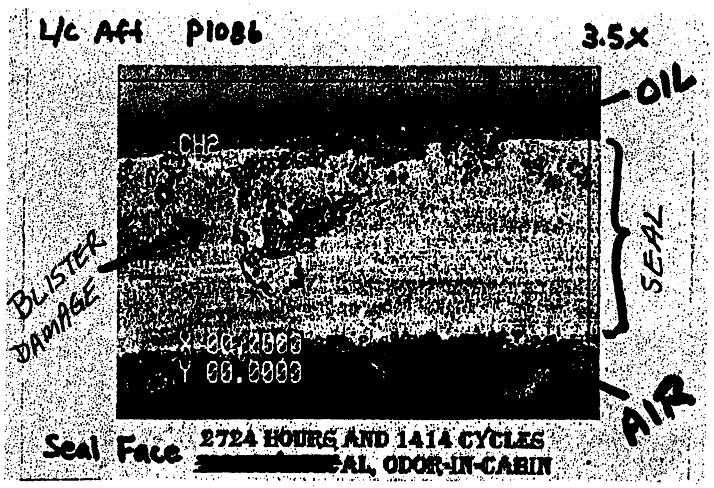
Carbon “Blisters” result in Material Removal, and can lead to Seal Leakage. They are typically Categorized into 3 Stages:

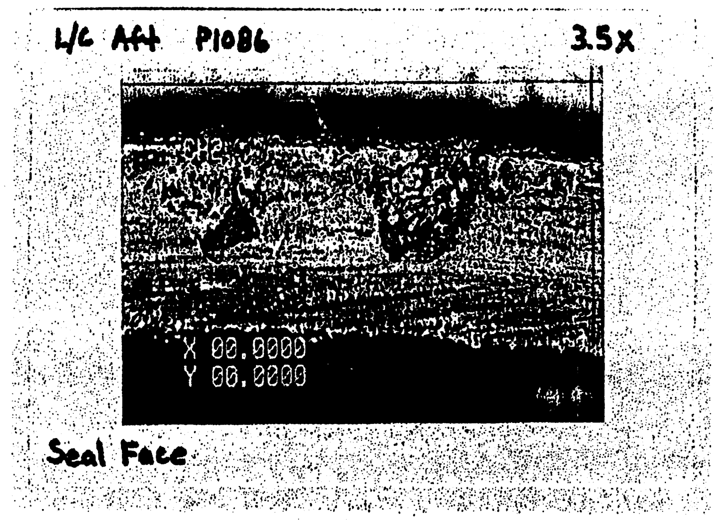


Picture of Blistered Carbon Seal

"Stages-3" Blisters from an Aircraft APU Seal ...

This seal was Leaking Oil and Causing "Odor in Cabin" for a Passenger Aircraft





1997-1998 Program Objectives

(1) "<u>Rank</u>" Carbon-Graphites for Blister-Resistance

(2) Determine Carbon Key <u>Properties</u> governing Blistering

(3) Identify Blister <u>Mechanism</u>

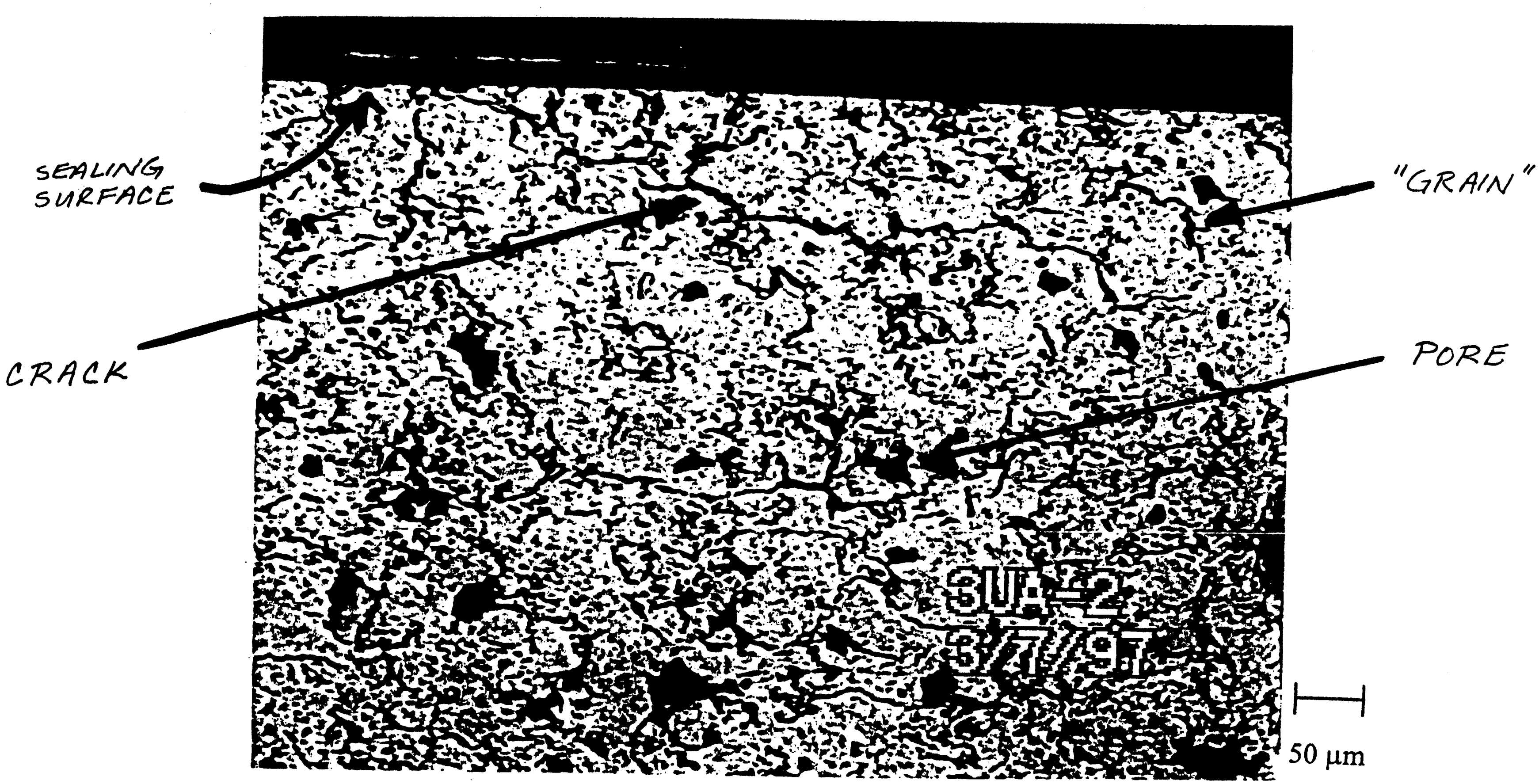
MicroStructure of Carbon-Graphite

- Carbon-Graphites have many natural “Flaws”: Pores; Cracks that link the pores, etc.

- Analysis of Blistered Seals focused on Sub-surface and Surface Cracking associated with each Blister

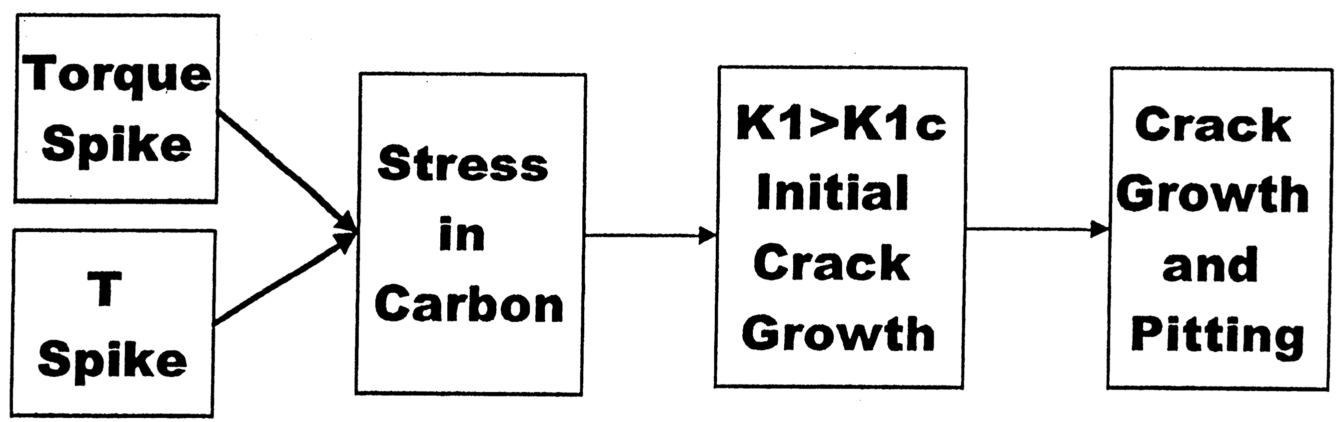
➡ **Found that “Fracture Toughness” is important to forming Blisters ... Specifically, Short Crack Toughness**

Example of MicroStructure of Carbon-Graphite



CROSS SECTION (Used Seal)

A Likely Blister Generation Process



Modeling Blister Theories

- **Hypothesis #1:** Crack Driving Force due to <u>transient Temperature Rise</u> ... from Unrelieved Oil Expansion inside Carbon

- **Hypothesis #2:** Crack Driving Force due to transient <u>Torque Spike</u> ... e.g. Transient Contact; Impactive Shear from Frozen Oil, etc.

AlliedSignal "Blister Rig" & "Test Method"

Objective: Produce Measurable Blisters ... "Repeatably"

Test Method:

- 1" Diameter Face Seal (Air on ID, Oil on OD)
- Air-side at Ambient conditions
- Oil-side "Flooded" with Very Cold Oil (typ -80F)
- High Face Load; Coated Seal Rotor
- Seal Chilled to -40F, then Accel from 0-to-64,000 rpm in 12 seconds
- Shutdown 10 seconds after Full-speed is reached
- Repeat Cycles (Cyclic operation produces Blisters)
- Run Specified Number of Cycles
- Measure Blisters

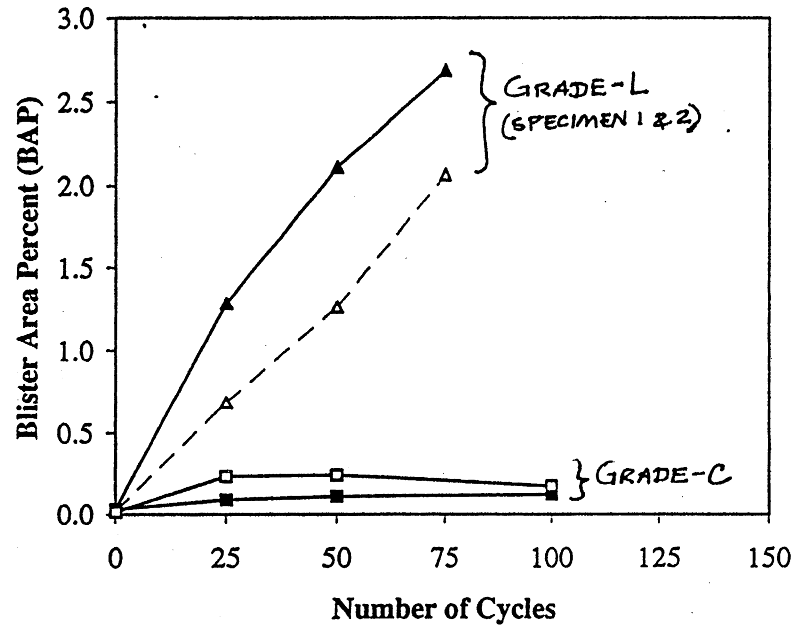
AlliedSignal "Blister Measurement" Method

- Method is Simple, and avoids "subjectivity"
- With Optical Microscope & Digital Micrometer, Measure Stage-3 Blisters (open pits), using Elliptical Area Approximation
- Locations also Recorded

<u>Define:</u> "Blister Area Percent", **BAP** $= (\Sigma \mathbf{A}_{\mathbf{Blister,i}})/A_{\mathbf{nose}}$

Test Method was Found "Repeatable" for a Range of Carbons

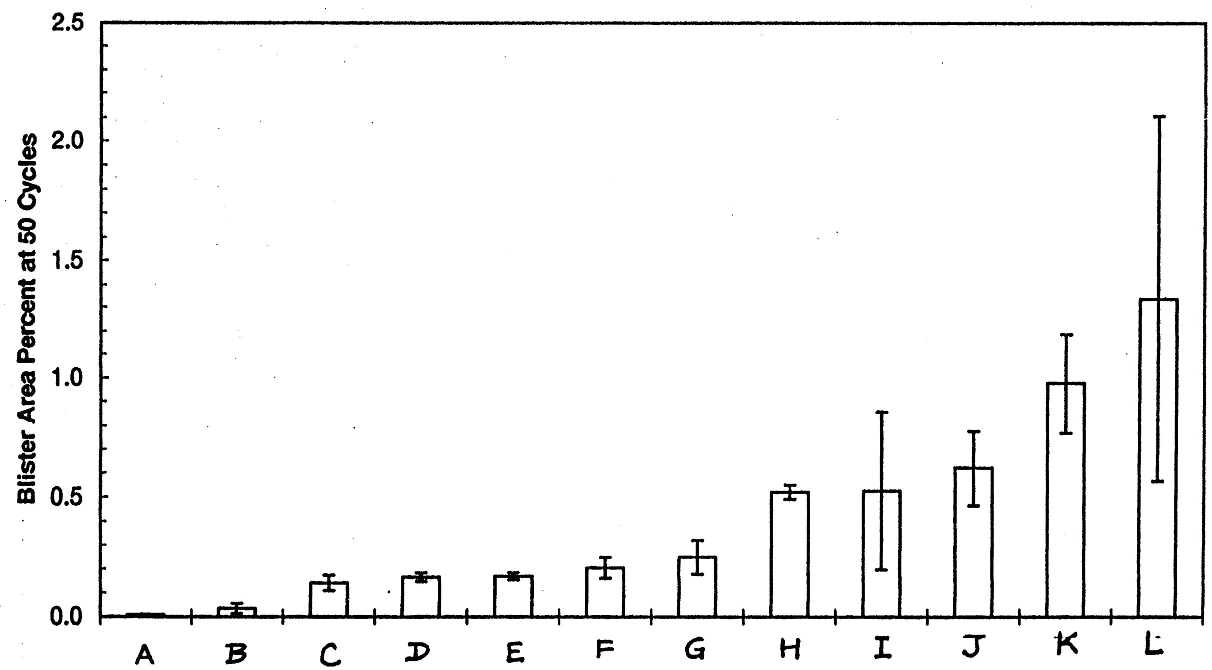
Blister-Resistant versus Blister-Prone Carbons were tested



Selected Carbon-Graphites were "Ranked" for Blistering Tendencies

<u>Candidate Selection based on:</u>

Grain Size & Uniformity; Impregnants; Toughness; Permeability; Experience; Vendors; etc.



Interim Conclusions

- AlliedSignal has Demonstrated a Test Method to "Repeatably" Produce and Measure Blisters in the Lab
- Carbon-Graphite Microstructures Give Clues to Blistering Tendencies ... Specifically, "Finer-Grain" Carbons appear to be more Blister Resistant
- "Short Crack Toughness" Test Developed at AlliedSignal appears to Identify more "Blister Resistant" Carbons
- In Highly Controlled Tests: Some Carbons are Blister-Prone, While Other Carbons Show a High Degree of Blister-Resistance

Results from this Study have already shown Success in Preventing Blistering in Actual Engine Seals

"The MESSAGE"

- **AlliedSignal has Tested Blister-Resistance "Repeatably". We will use this internally to Identify & Use Existing Blister-Resistant Carbons. But more Carbons are needed to Meet Various Sealing Demands, So ...**

- **AlliedSignal Wants to Encourage <u>Carbon Companies</u> and <u>Seal Companies</u> to Utilize AlliedSignal's Study and Perform their Own Studies, and Produce more Blister-Resistant Seals**

EXPERIMENTAL AND NUMERICAL RESULTS FOR A LIQUID HYDROGEN TURBOPUMP WITH SEAL CAVITIES

K.N. Oliphant, A. Bhattacharyya,
and David Japikse
Concepts ETI
White River Junction, Vermont

Effective sealing in secondary flow paths is critical to the performance of rocket turbopumps. It is important to be able to predict seal performance and the interaction of seal flows on the main flow in order for the designer to properly assess the impact of a particular seal design on the overall system performance. This paper presents the results of a series of Computational Fluid Dynamics (CFD) calculations of the First Stage SSME ATD LH2 Rocket Turbopump with seal cavities and compares the CFD results to experimental data over a range of operating points.

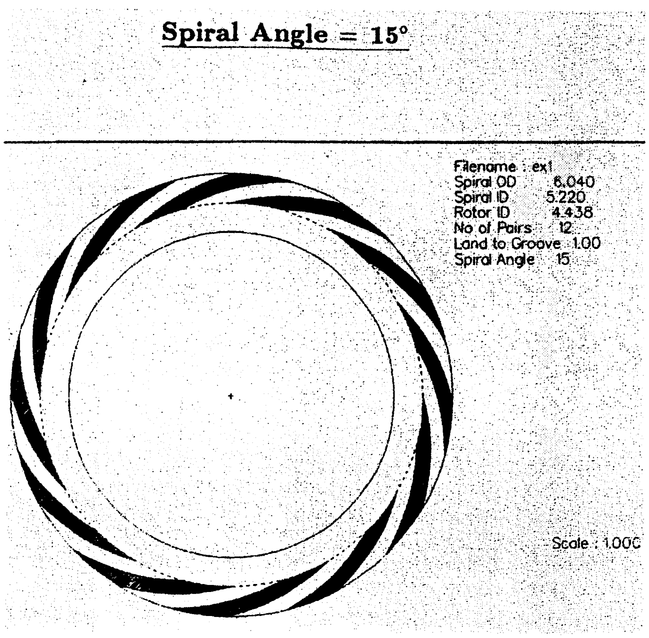
It was seen that the CFD could predict the trends in the experimental data although the exact pressure drop through the seal cavity was not predicted. It was surmised that the discrepancy was due to the turbulence model that cannot capture the complex stress-strain fields that are present in the seal cavity.

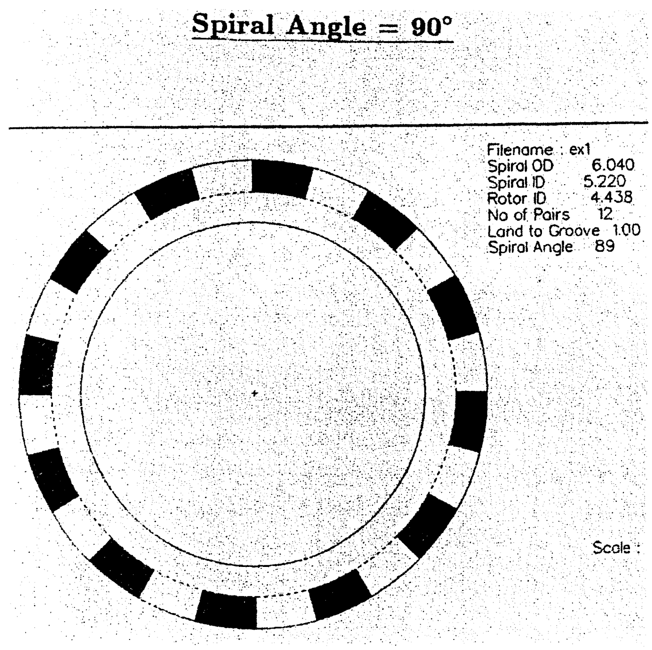
In addition, the CFD calculations indicated that the location of the seal cavity flow injection into the impeller eye region could be an important design criterion for both the seal cavity and the impeller. The pressure disturbance from the presence of the impeller leading edge caused the flow to locally reverse direction from the expected direction and went back into the seal cavity. More study is required to investigate this phenomenon and determine its effect on the system performance.

SEAL TECHNOLOGY DEVELOPMENT AT EG&G ENGINEERED PRODUCTS

Ray England
EG&G
Cranston, Rhode Island

Liftoff Geometries





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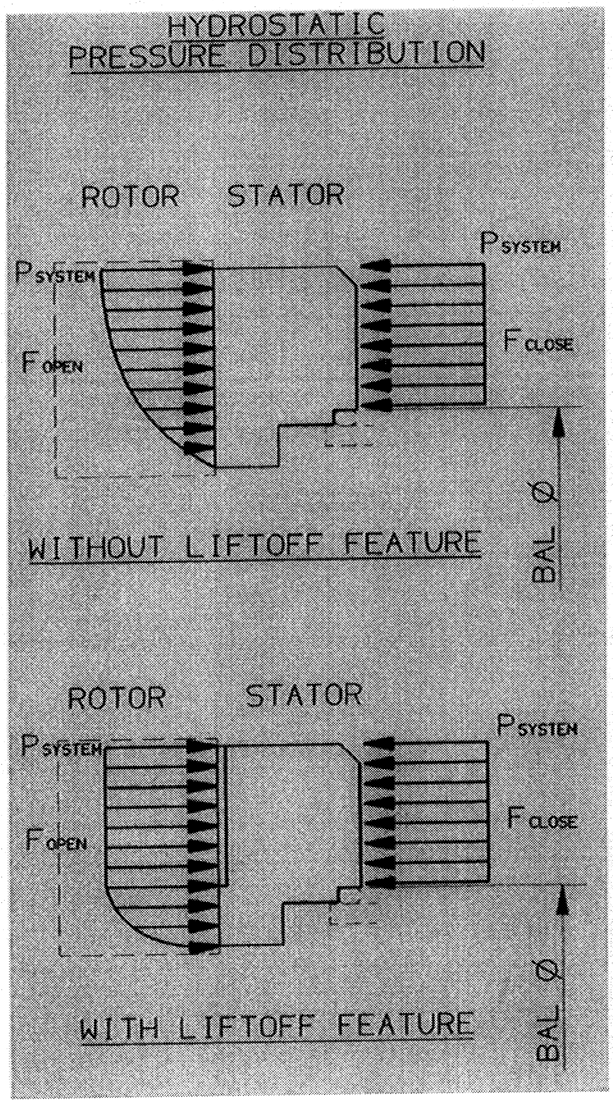
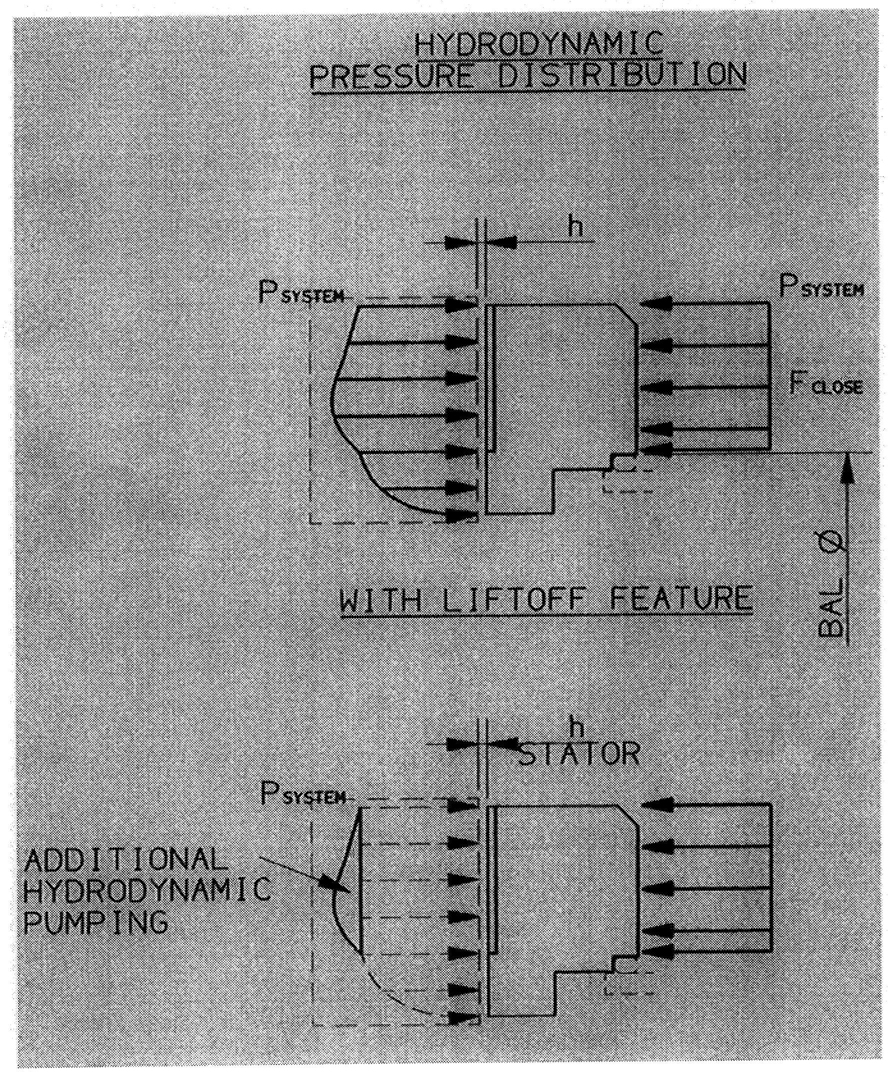
Gas Face Seal Theory





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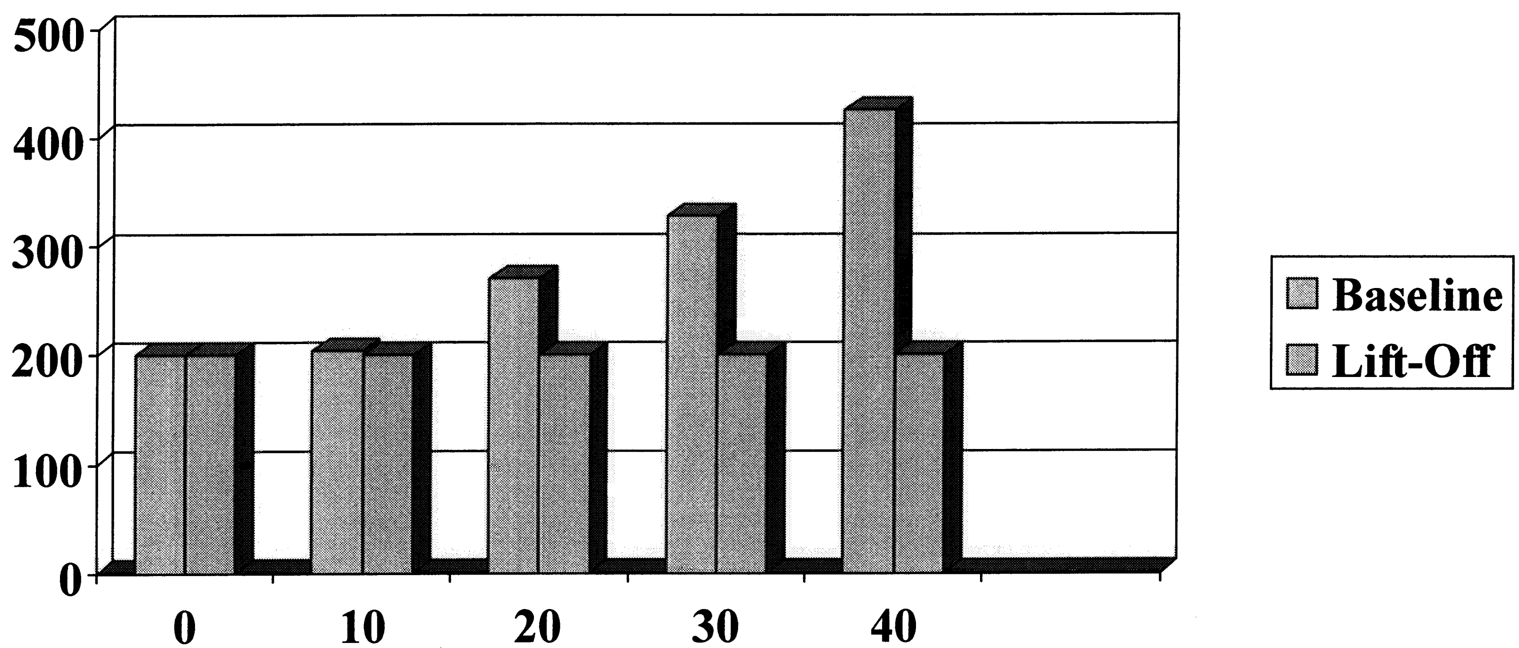
Test Results

Dry Tests (30 psig)



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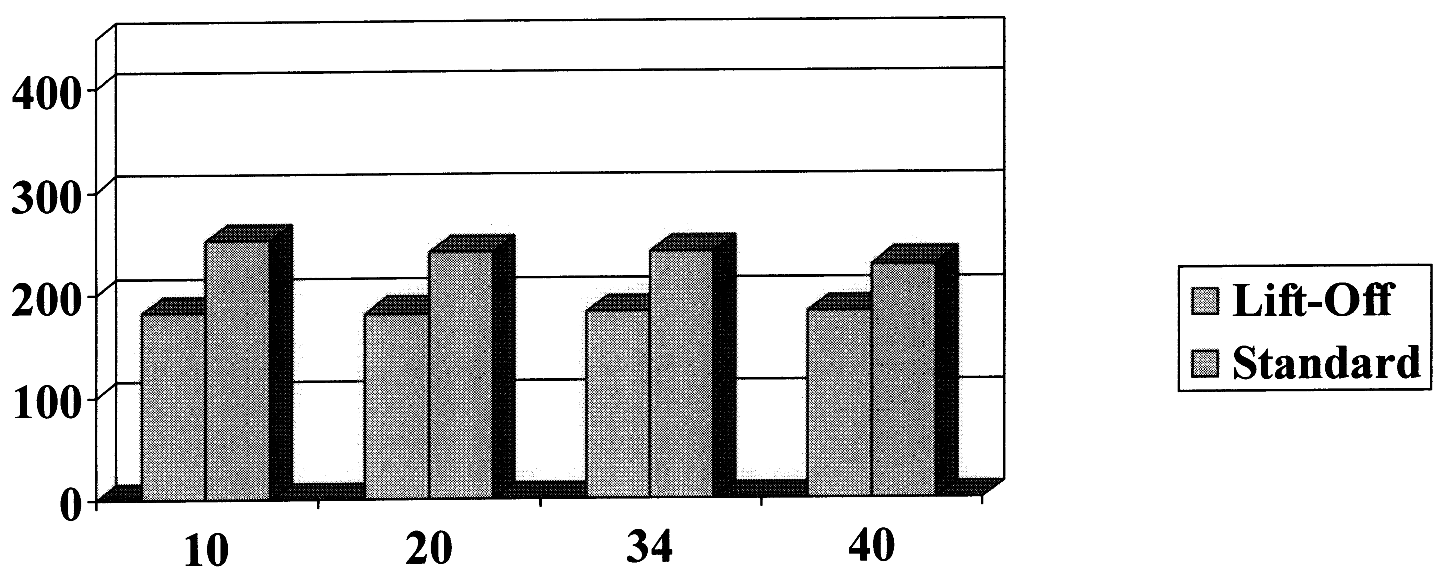
Test Results

Oil Tests (30 psig)



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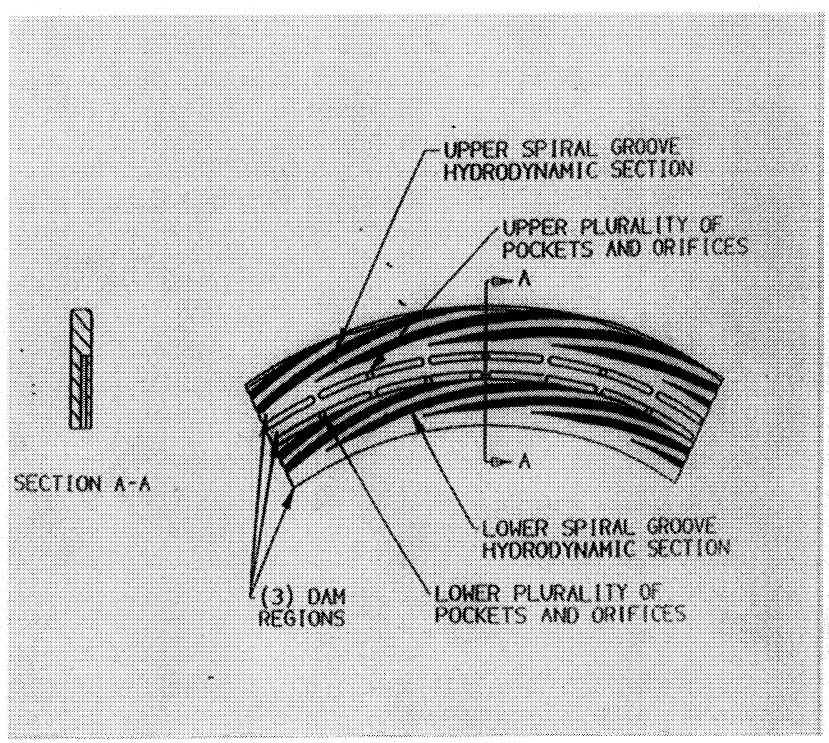
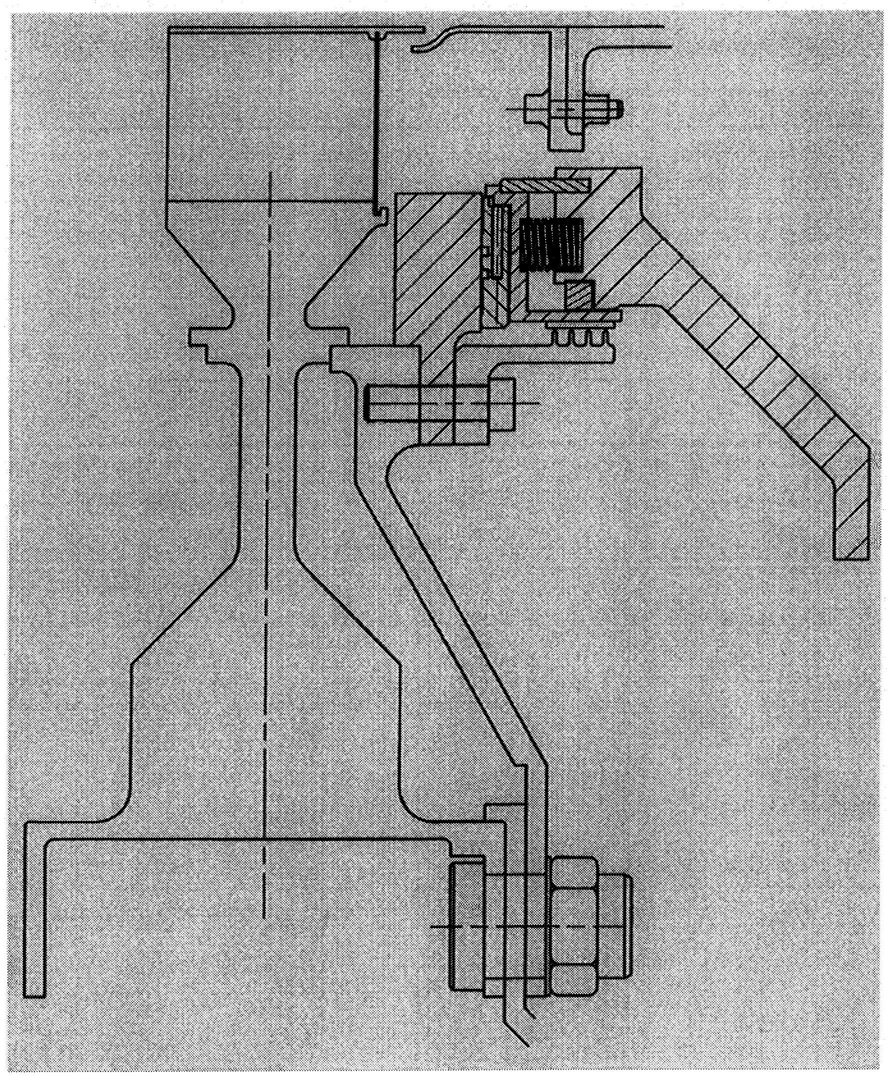
High Angular Compliance Gas Seal



- Double Spiral/Radial Groove Face Seal to Accommodate Extreme Rotor Coning
- 300 -400 psi, 500-1000 fps
- All Metallic Construction
- Compressor Discharge, Balance Piston Seal



Compressor Discharge Application

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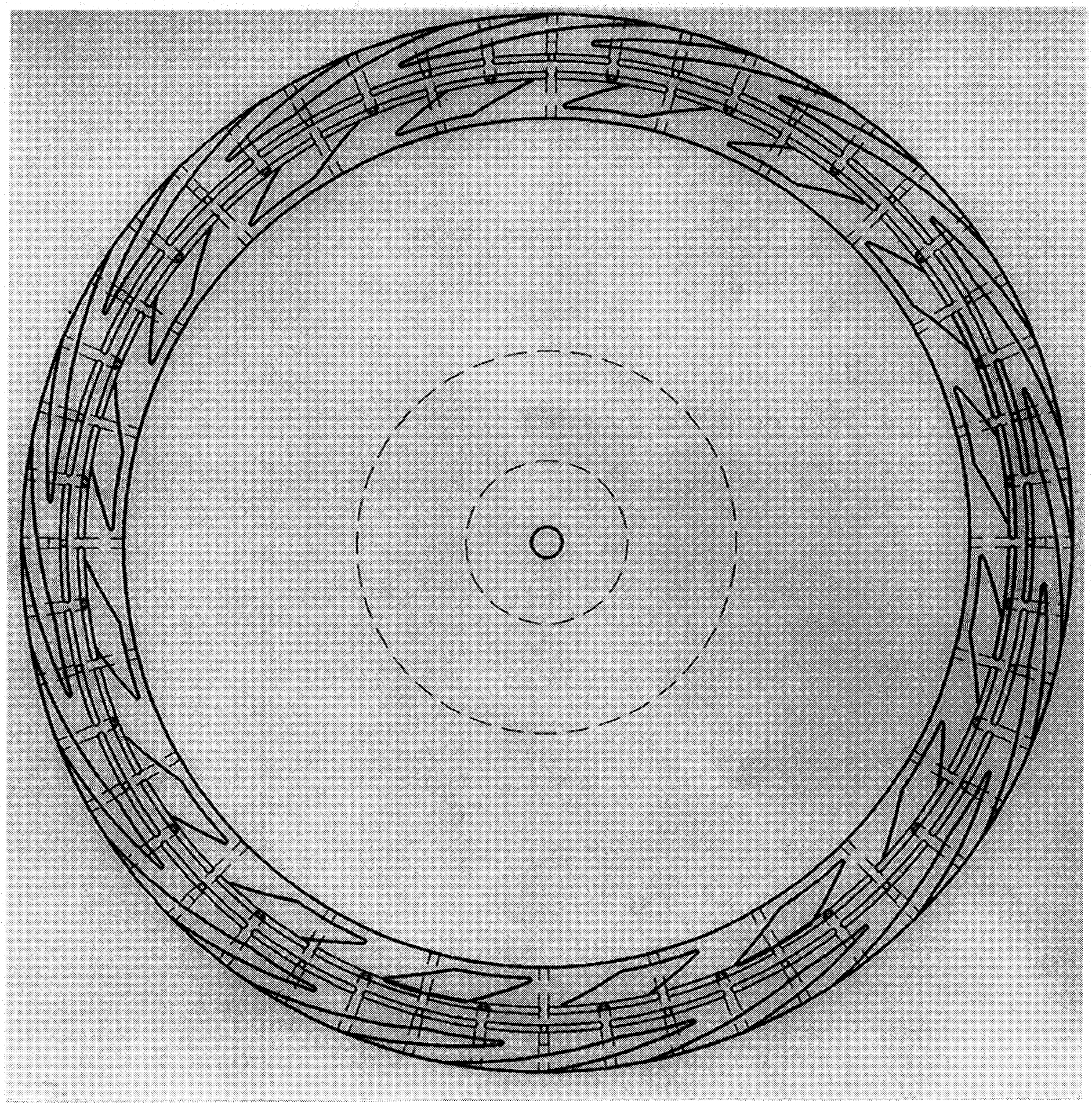
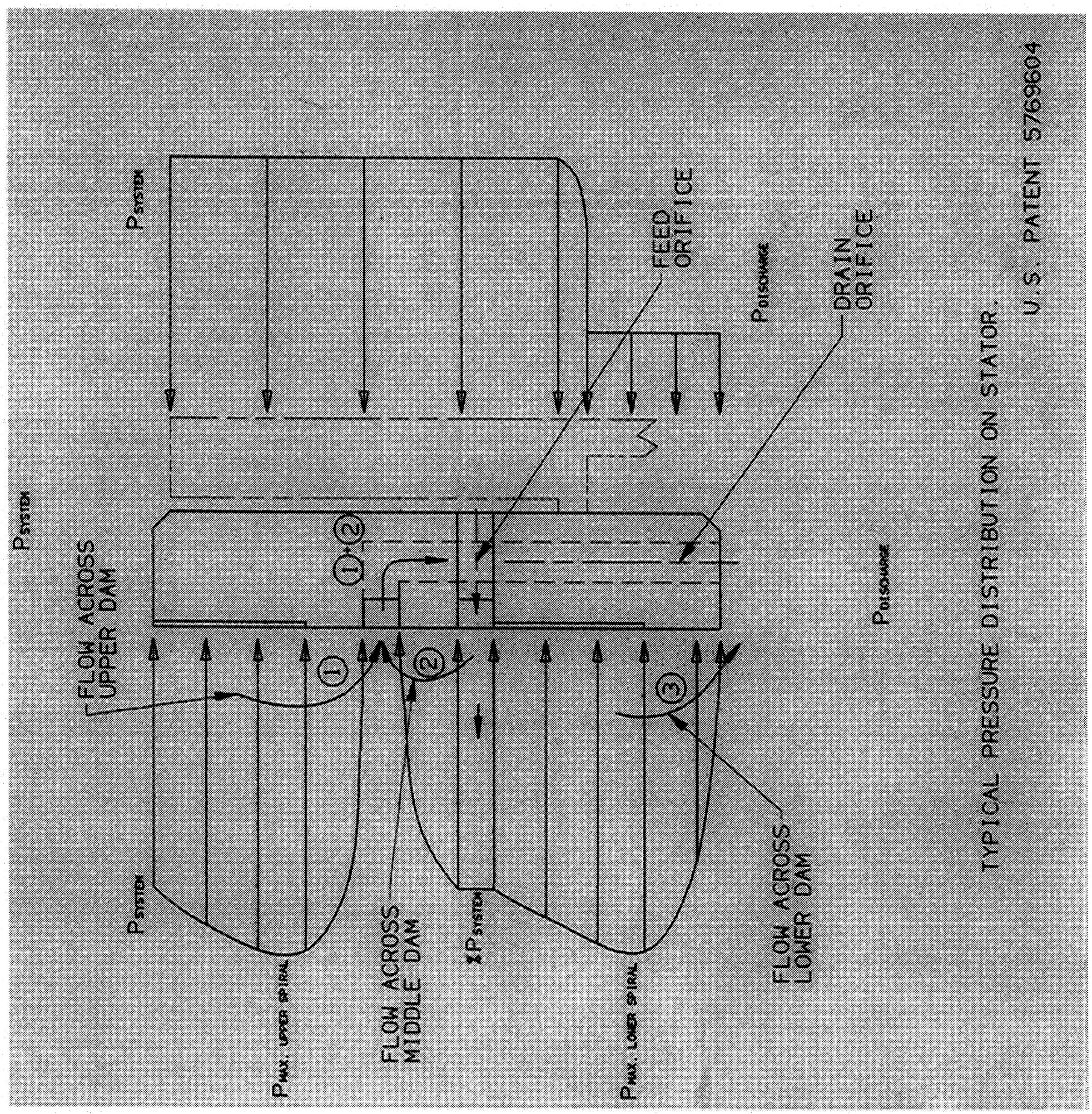
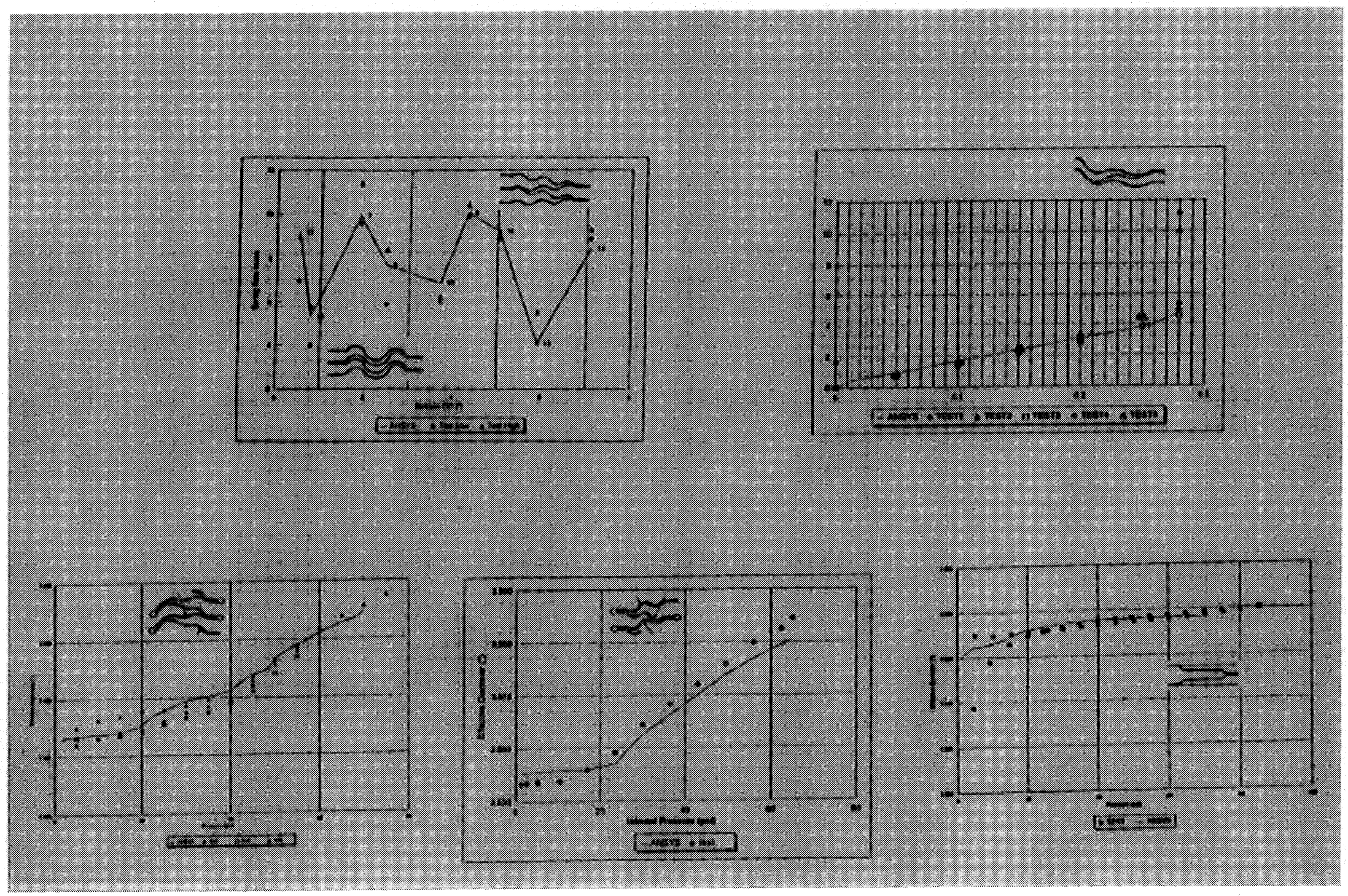


Dual Spiral Groove Geometry



FLOW ACROSS UPPER DAM
FLOW ACROSS MIDDLE DAM
FLOW ACROSS LOWER DAM
FEED ORIFICE
DRAIN ORIFICE
P SYSTEM
P DISCHARGE
P MAX. UPPER SPIRAL
P MAX. LOWER SPIRAL
% P SYSTEM
1
2
3
1+2
TYPICAL PRESSURE DISTRIBUTION ON STATOR.
U.S. PATENT 5769604

Mechanical Properties Prediction: Spring Rate; ED shift



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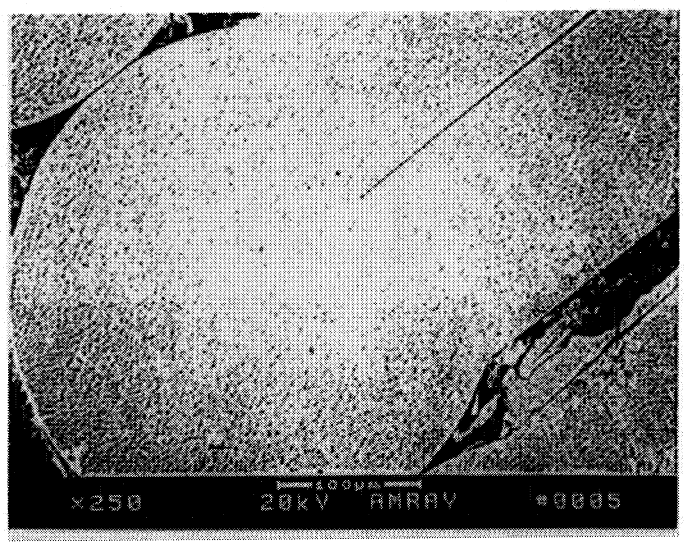
High Cycle Fatigue Design

- Prevention



- <u>Welded Structures</u>
- Metallurgically Nonhomogeneous
- Unheated Parent Metal
- Heat-Effected Zone
- Welded Metal (Cast)
- <u>Sharp Notch</u>
- <u>Thin Shell Structures</u>

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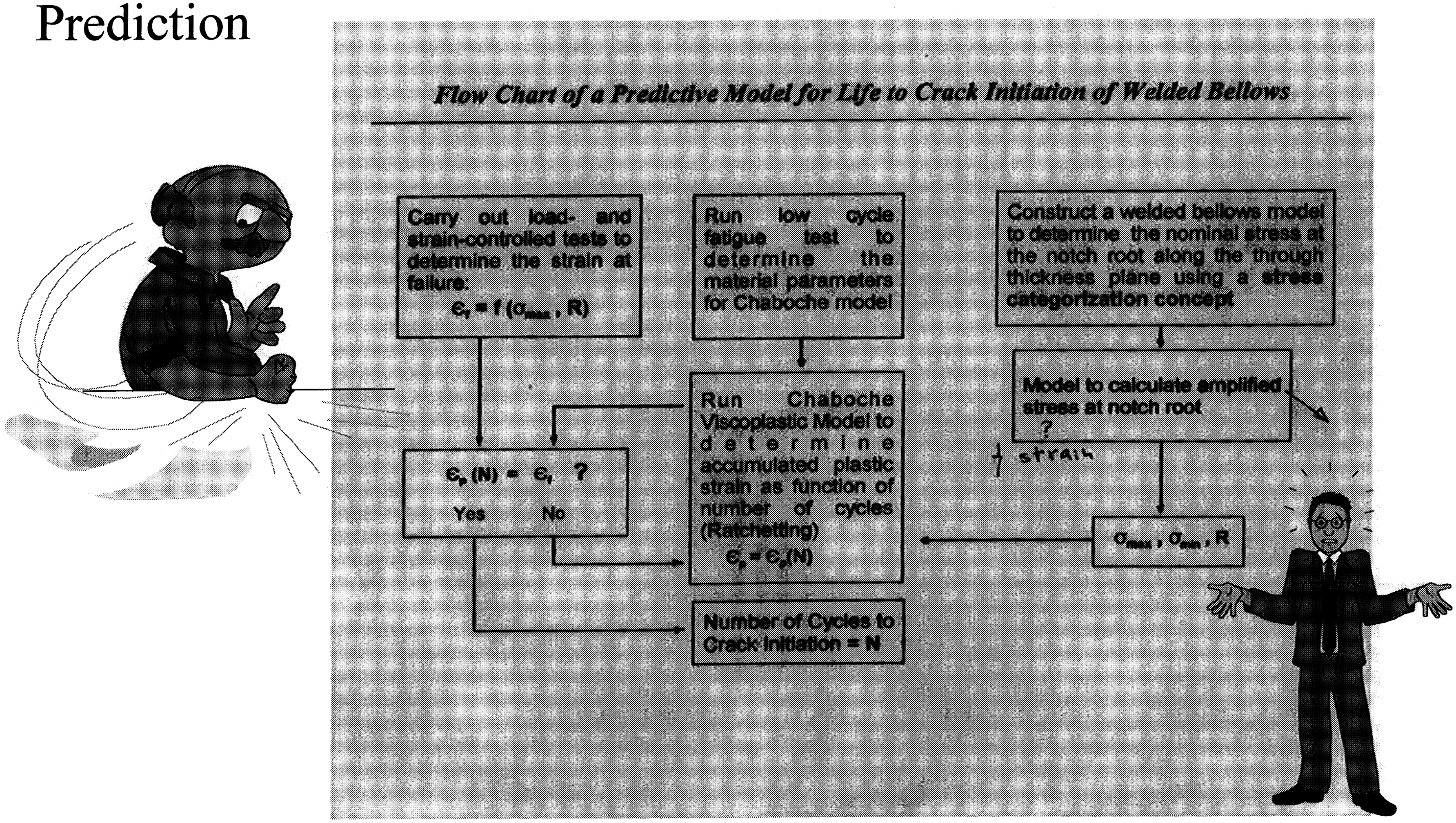
Low Cycle Fatigue Design

Prediction



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Historical Development

- Industrial Gas Seal Development Since 1987
- Radial and Spiral Groove Geometries
- In-House Fluid Mechanical Design Codes
- Seal Test Capability
- Low Pressure Medium Speed Development Since Mid-1996

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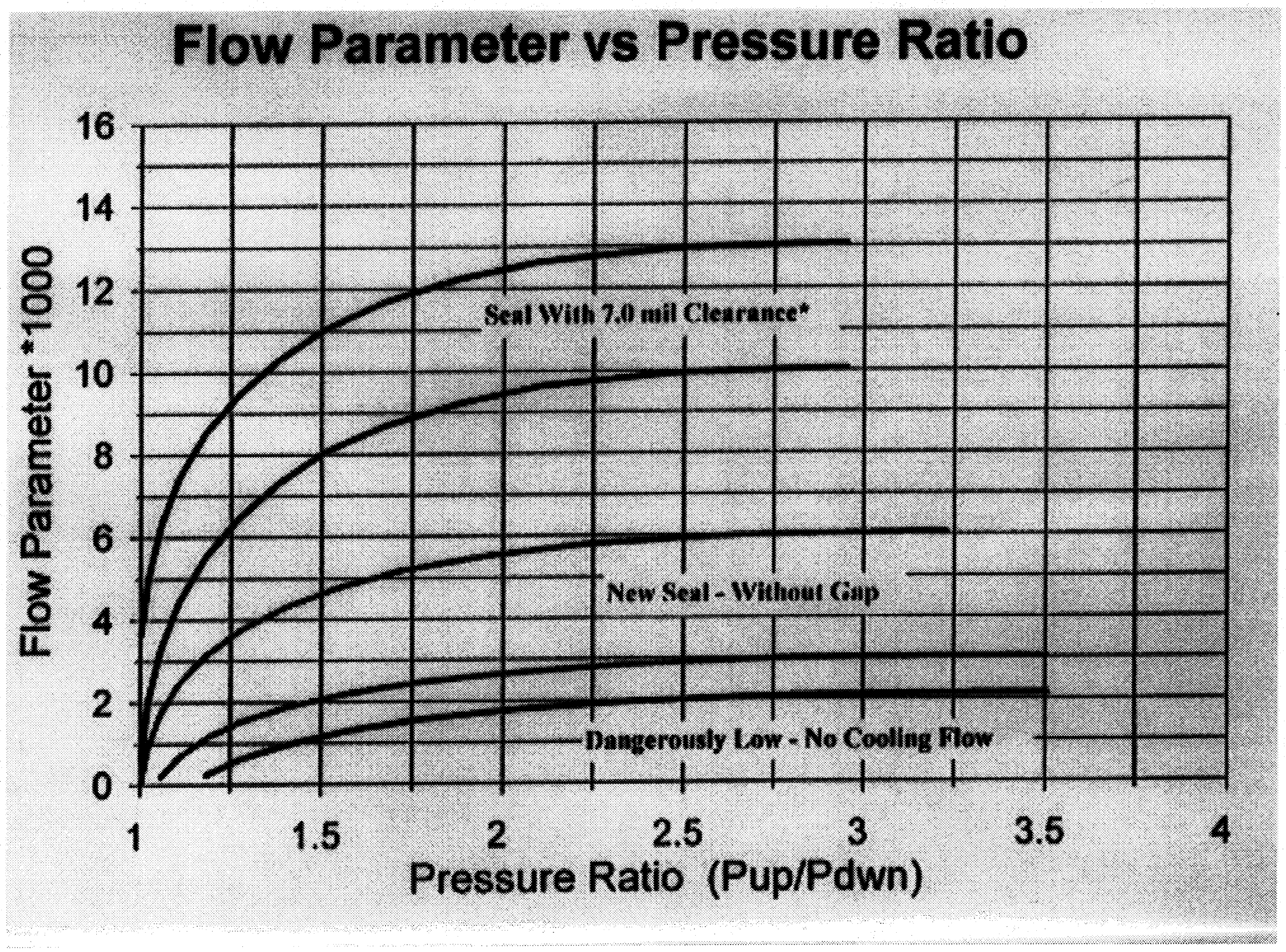
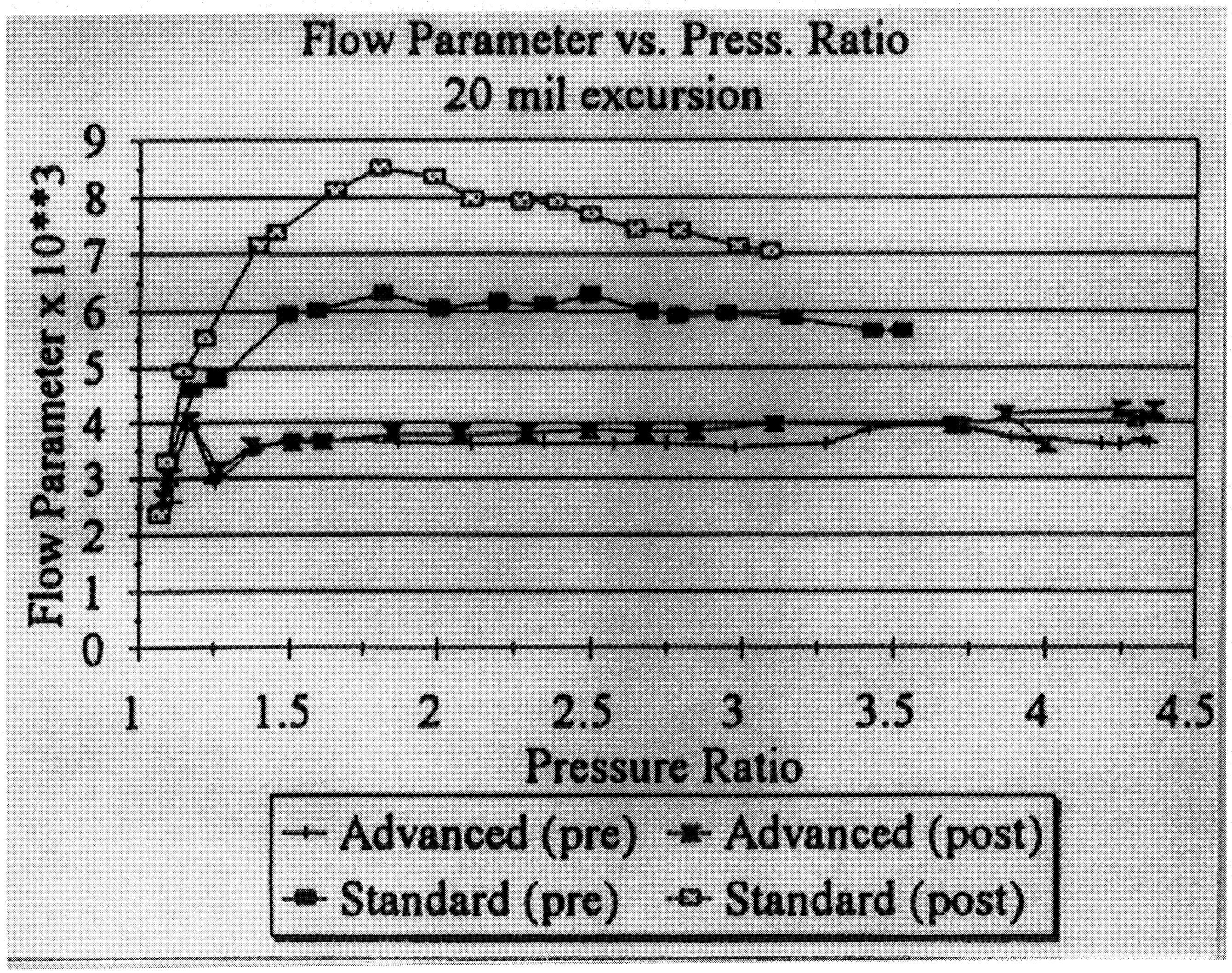
Predicted Leakage



Design Comparison



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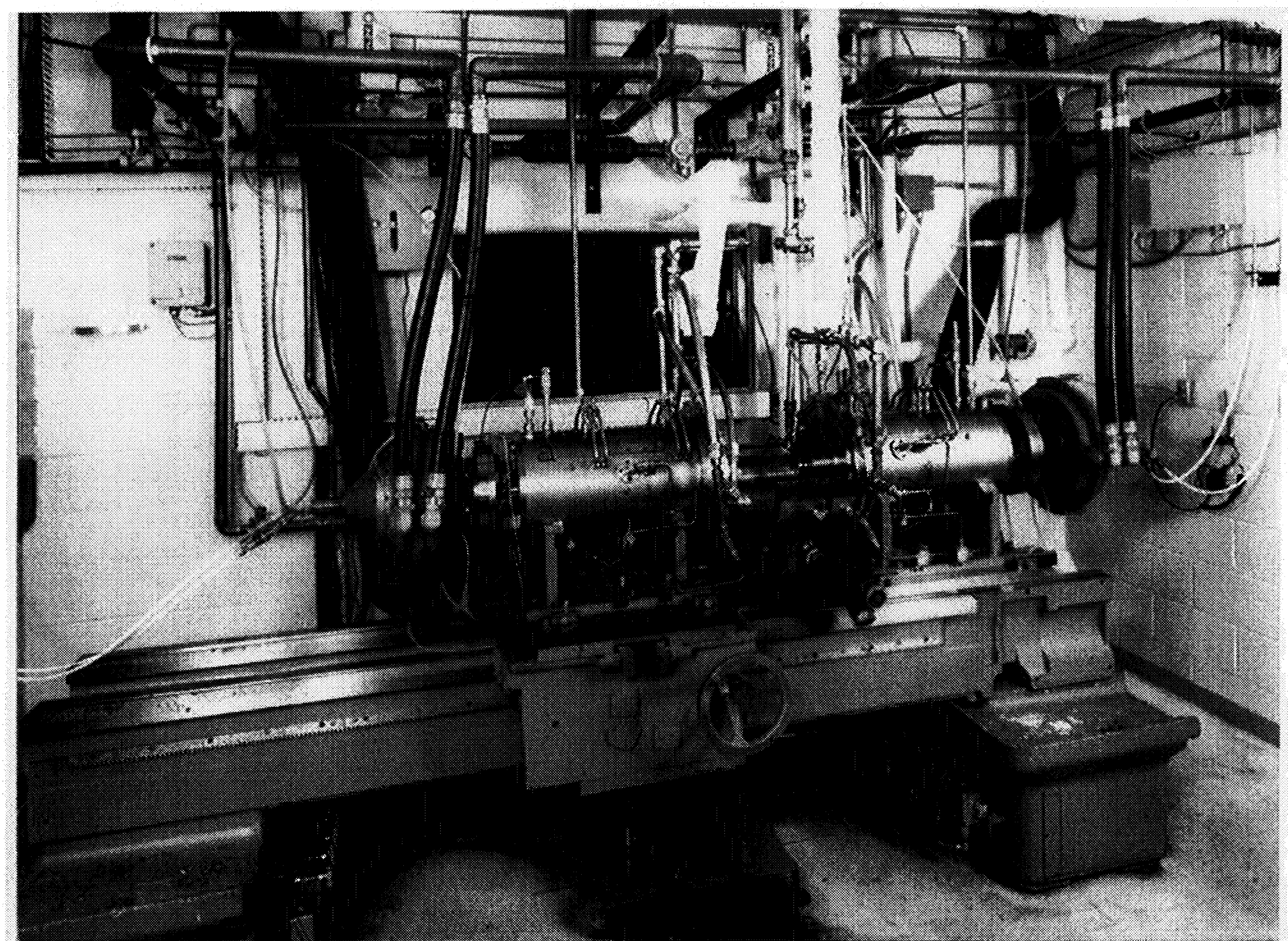
Aerospace Test Rig



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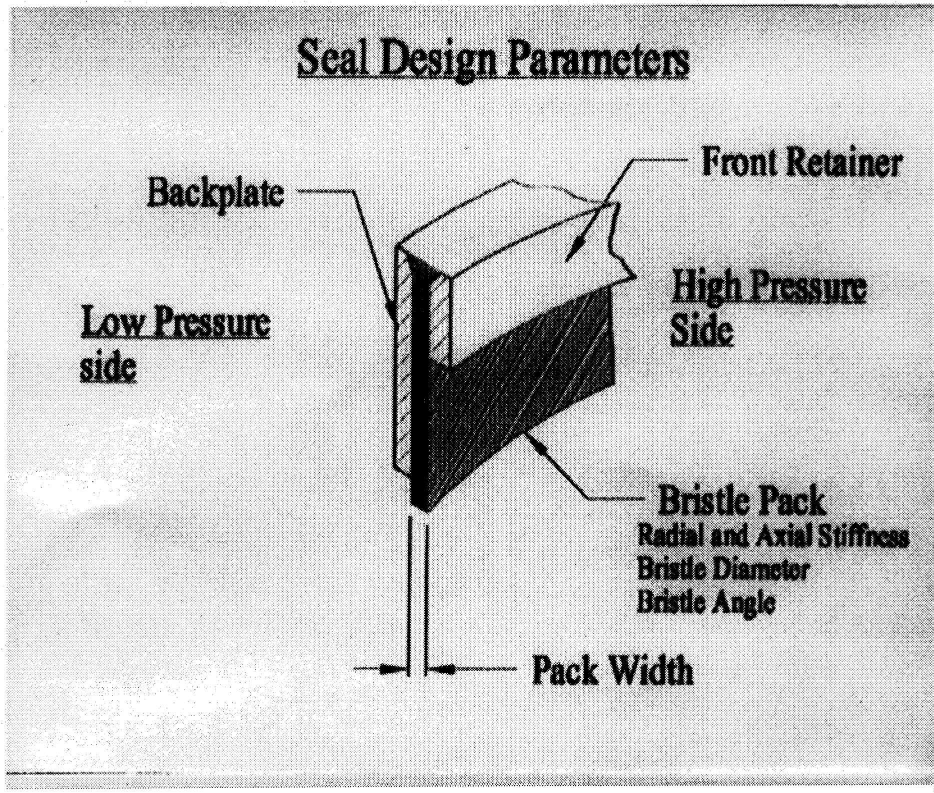
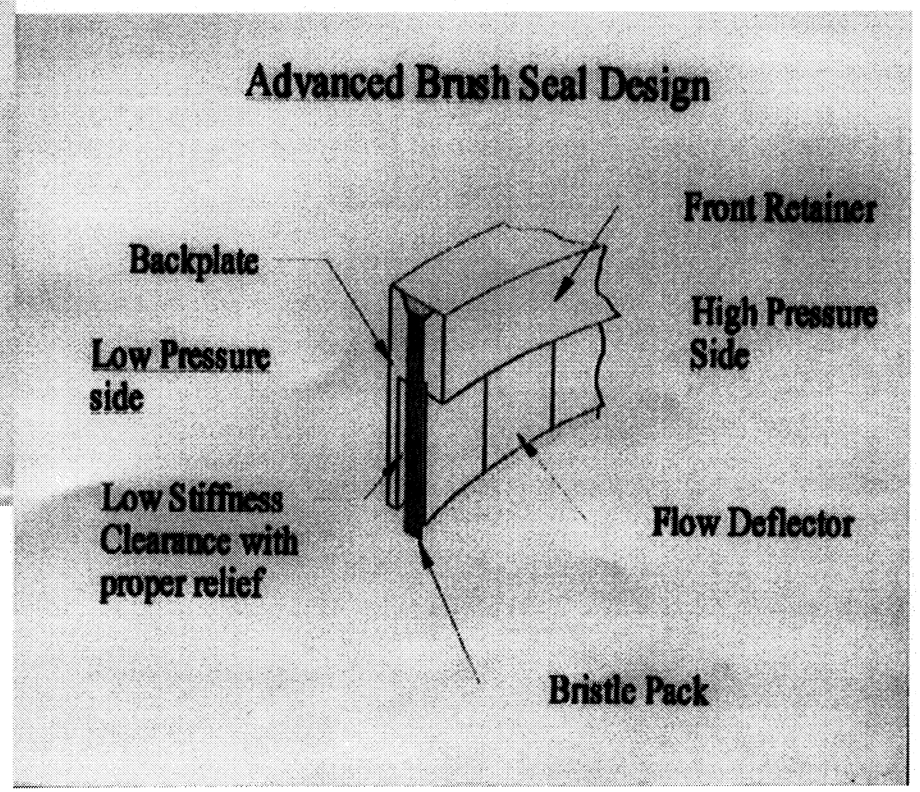
Standard and Advanced Designs





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Brush Seal Technology

- Aerospace
- Power Generation

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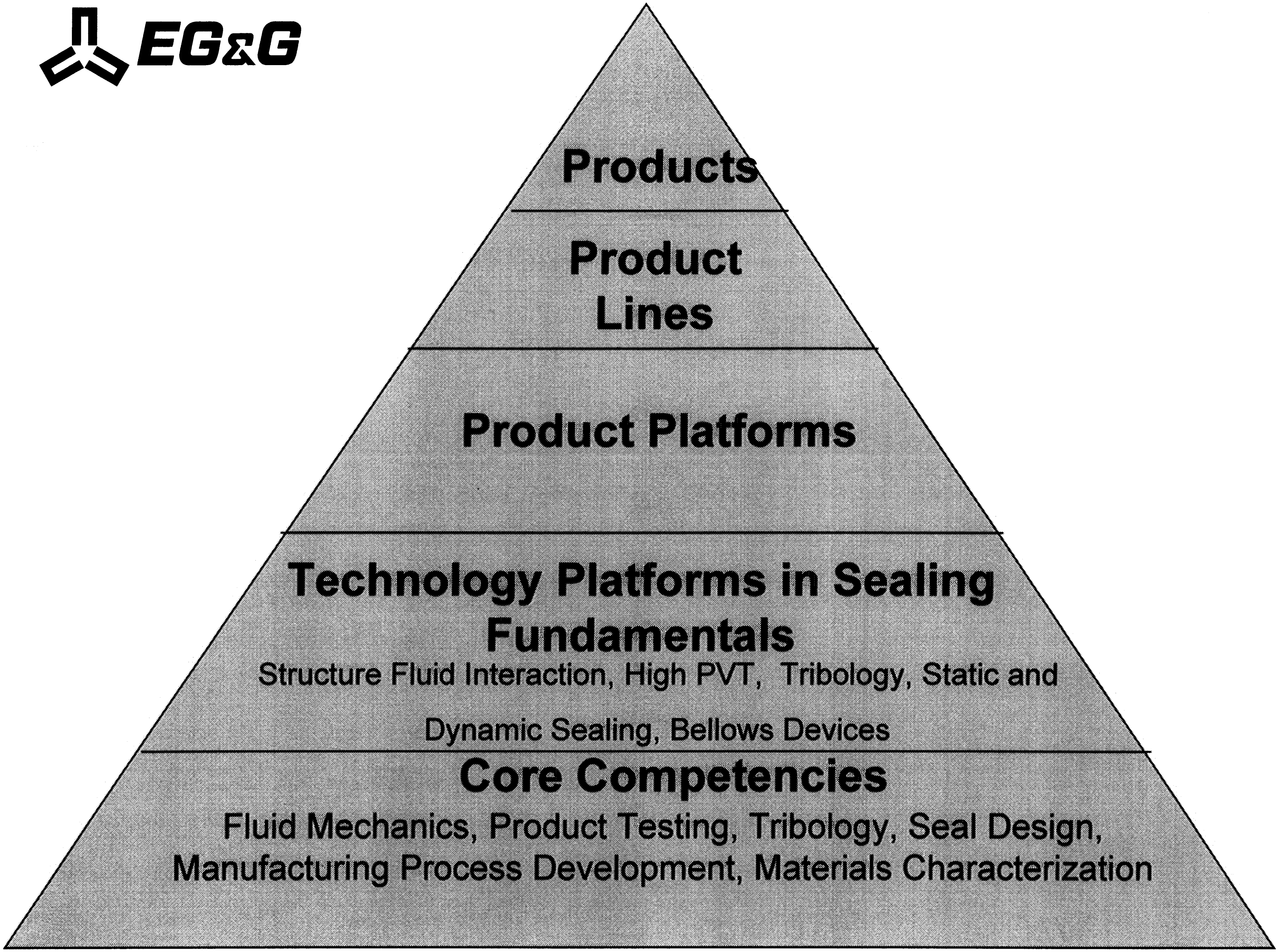

Products
Product Lines
Product Platforms
Technology Platforms in Sealing Fundamentals
Structure Fluid Interaction, High PVT, Tribology, Static and Dynamic Sealing, Bellows Devices
Core Competencies
Fluid Mechanics, Product Testing, Tribology, Seal Design, Manufacturing Process Development, Materials Characterization

SEAL DEVELOPMENT AT STEIN SEAL COMPANY

Alan D. McNickle
Stein Seal Company
Kulpsville, Pennsylvania

Outline

Seal Development Programs

- Hydrodynamic Circumferential Seals
  - Gas Seals
  - Oil Seals
- Hydrostatic Face Seals
  - Aspirating Seal
  - Stepped Face Seal
- Intershaft Seals
  - Hydrostatic Face Seal

Hydrodynamic Circumferential Seal Development

- Gas Seals
  - Aerospace Gas Turbine Applications
    - » High Pressure & High Speed
- Oil Seals
  - Land Based Gas Turbine Applications
    - » Generators

Hydrodynamic Circumferential Seals
Gas Seals
Program Goals

- Increase Pressure Differential Capability
- Increase Seal Wear Life
- Increase Seal Operating Speed
- Expand Circumferential Seal Applications

Hydrodynamic Circumferential Seals
Gas Seals
Operating Conditions

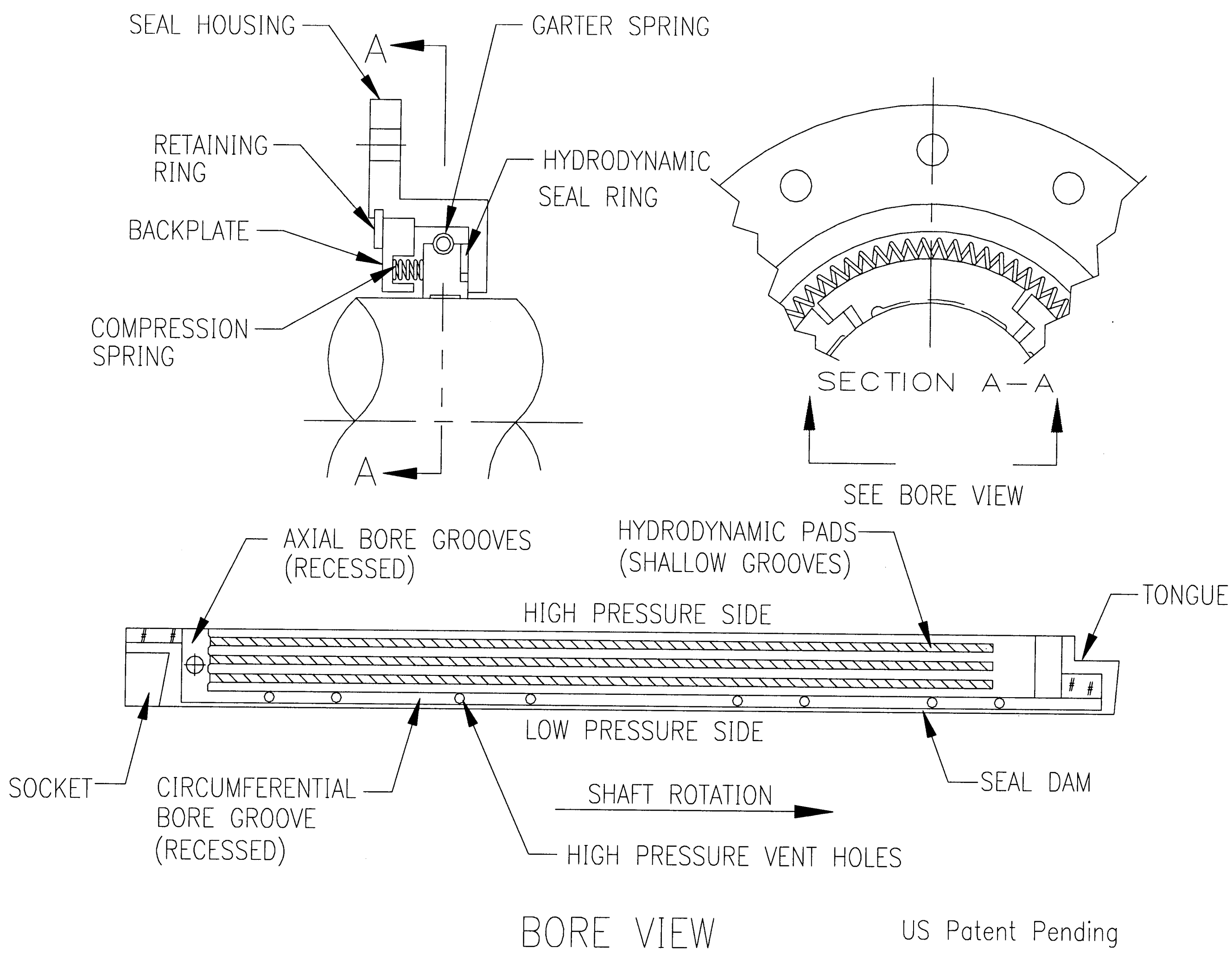
Current Technology
(non-simultaneous conditions)

- Shaft Speed: 465 ft./sec.
- Press. Diff.: 85 psid
- Air temp.: 850 °F
- Leakage: < 1.5 SCFM
- Seal Life: <10,000 hours

Hydrodynamic Circumferential Seal

- Shaft Speed: 600 ft./sec.
- Press. Diff.: 100 psid
- Air temp.: 750 °F
- Leakage: < 3.0 SCFM
- Seal Life: >20,000 hours

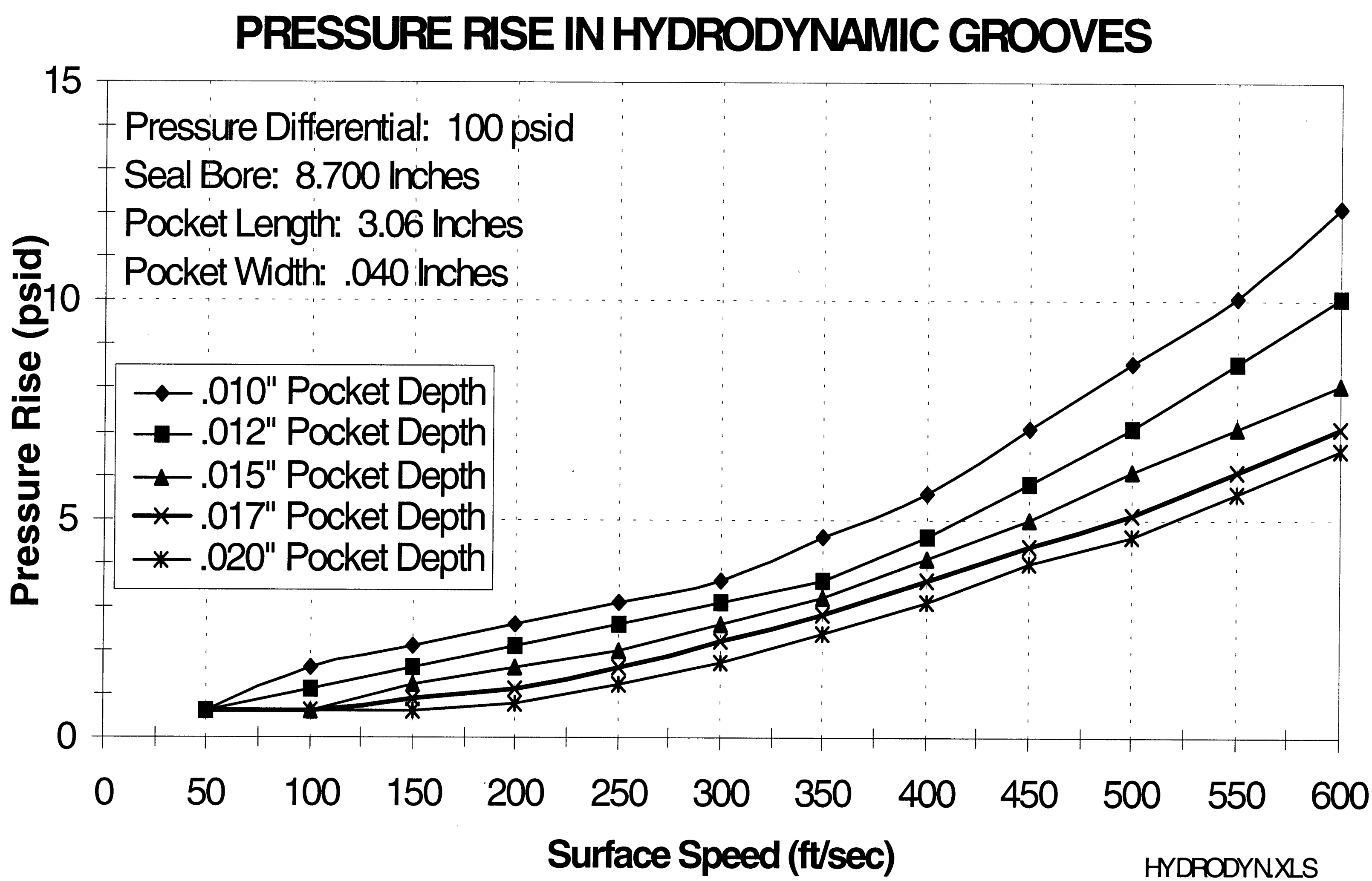
Hydrodynamic Gas Seal



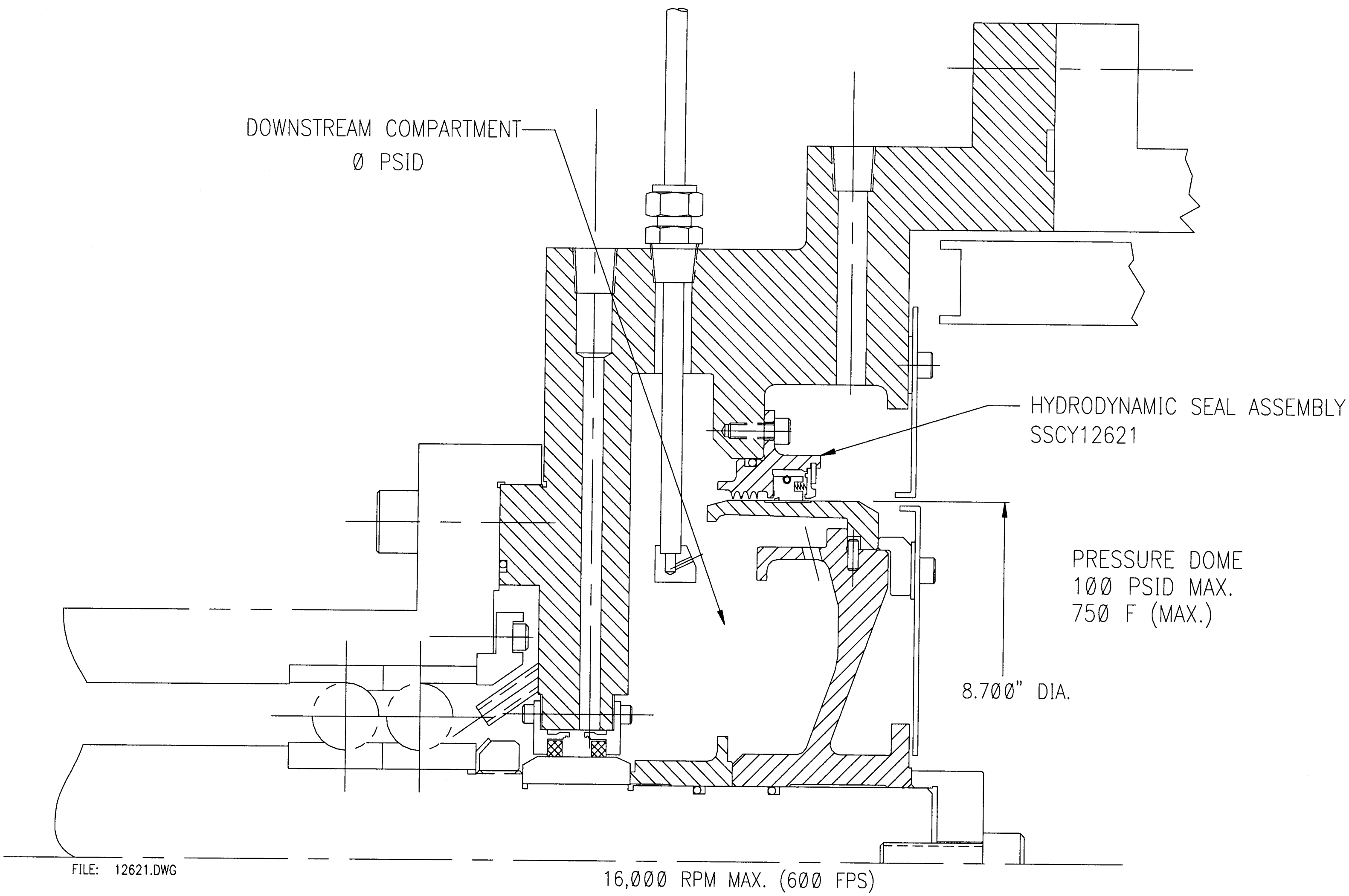
HYDRODYNAMIC SEAL ASSEMBLY
WITH LIFT POCKETS

H-D ASSY.DWG

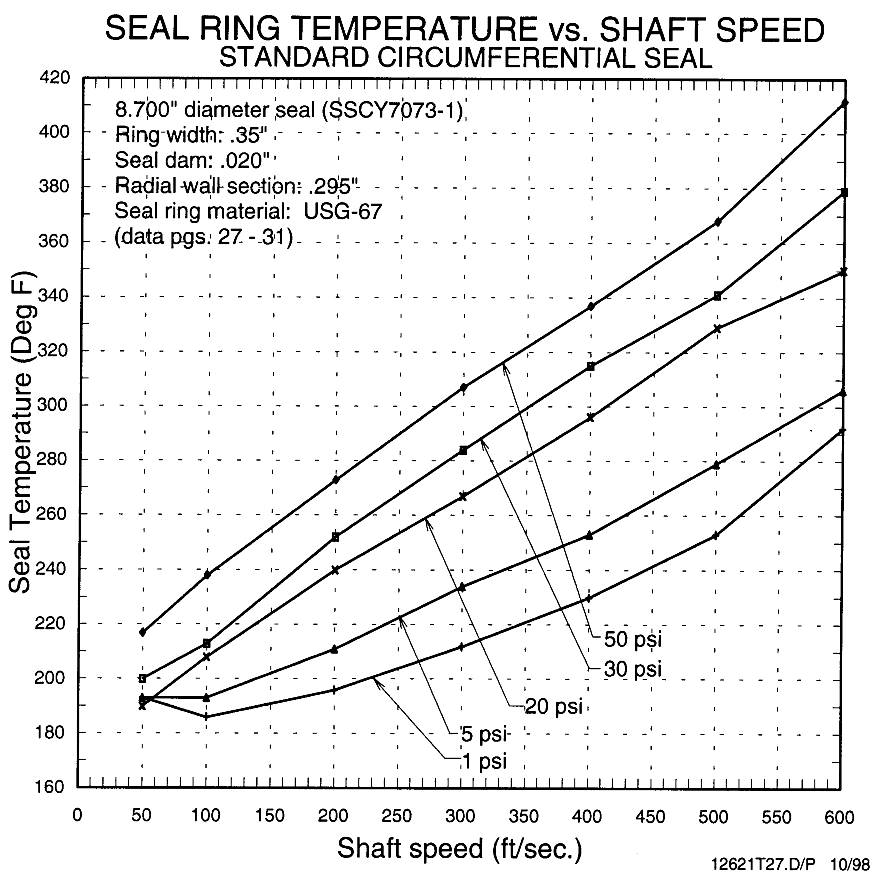
Hydrodynamic Gas Seal

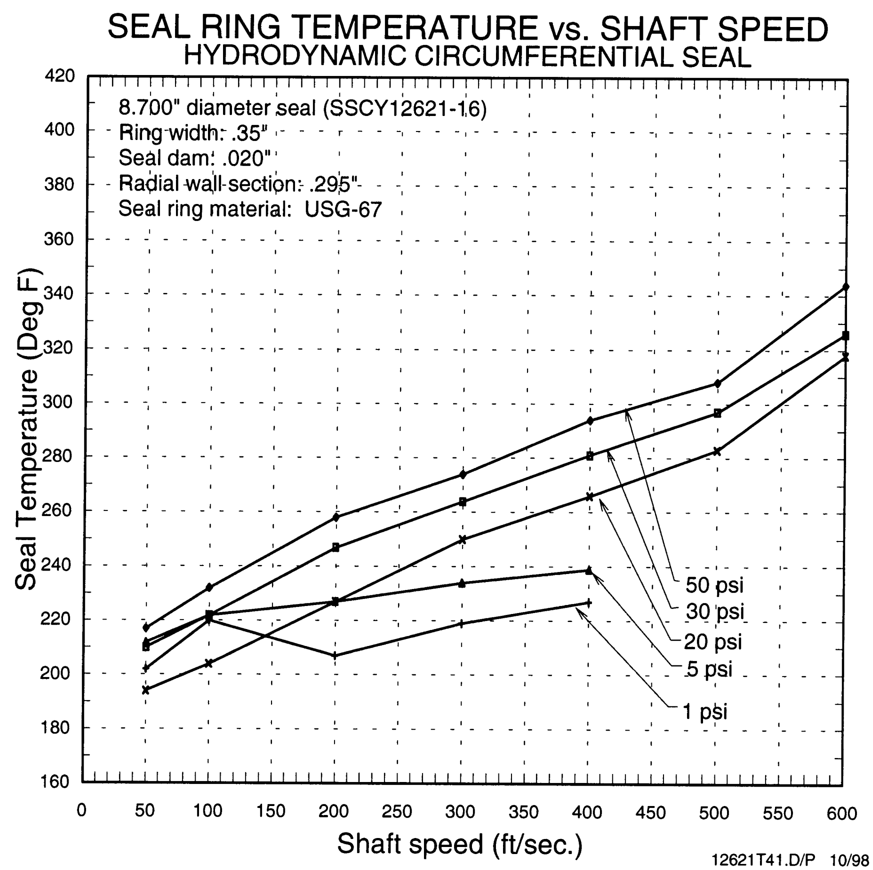


Hydrodynamic Gas Seal
Dynamic Test Rig



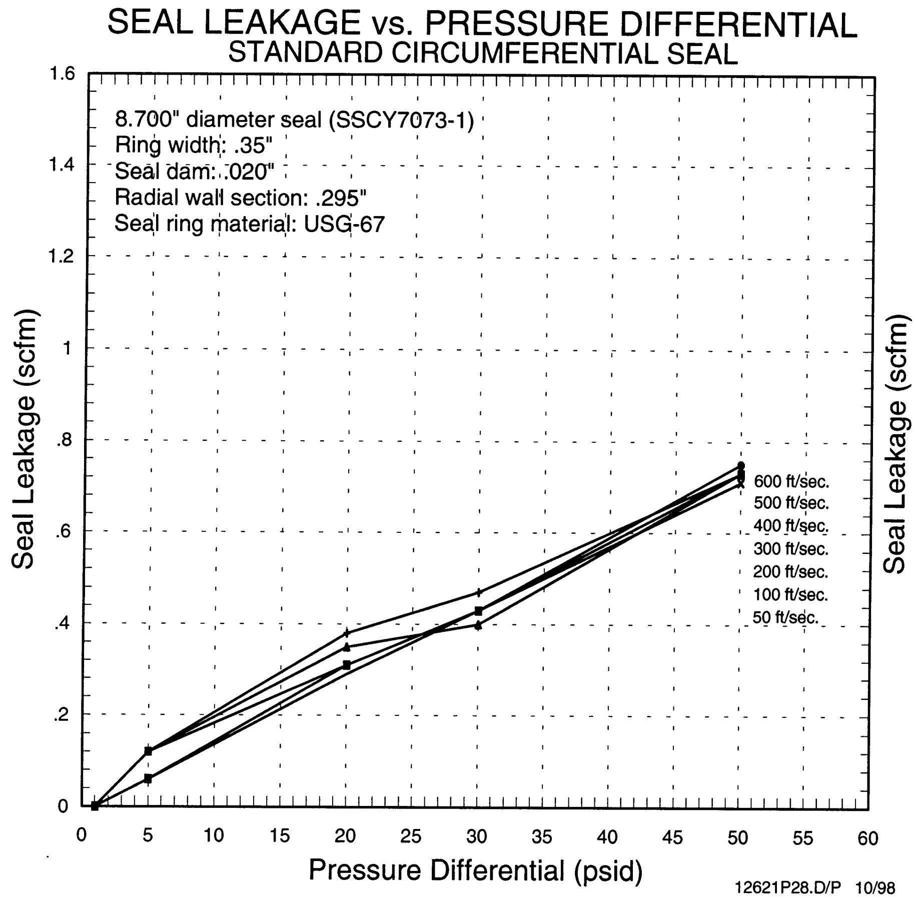
Dynamic Rig Test Results
Seal Ring Temperature vs. Shaft Speed

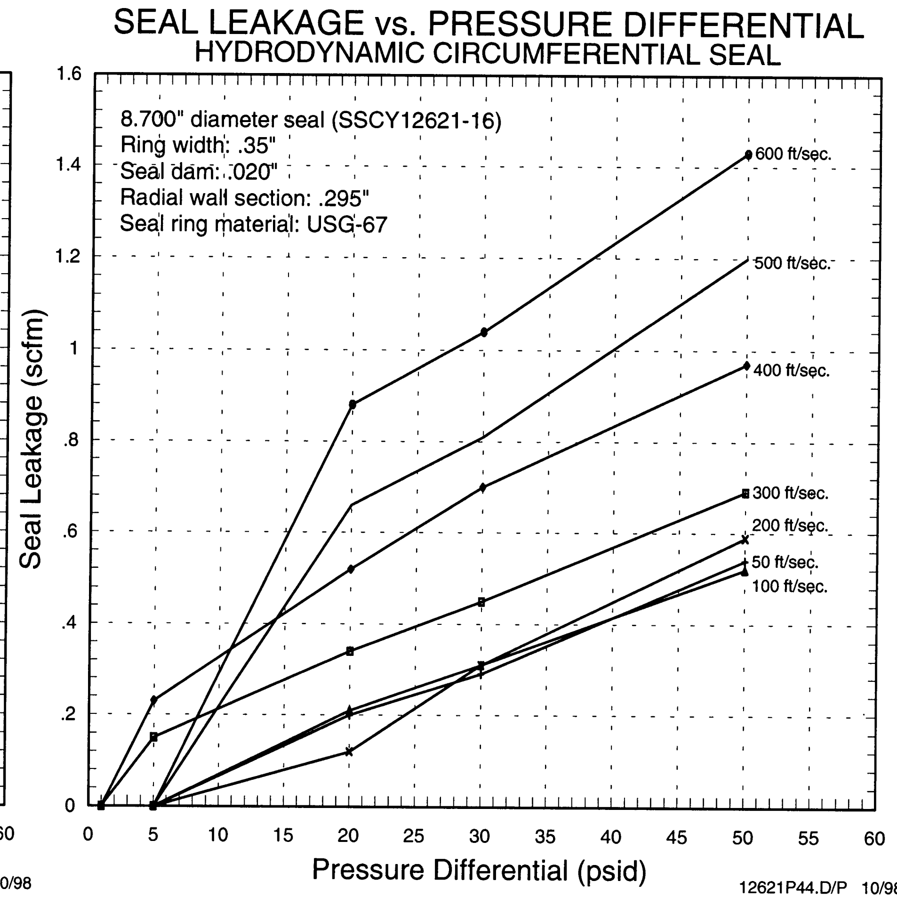




Dynamic Rig Test Results

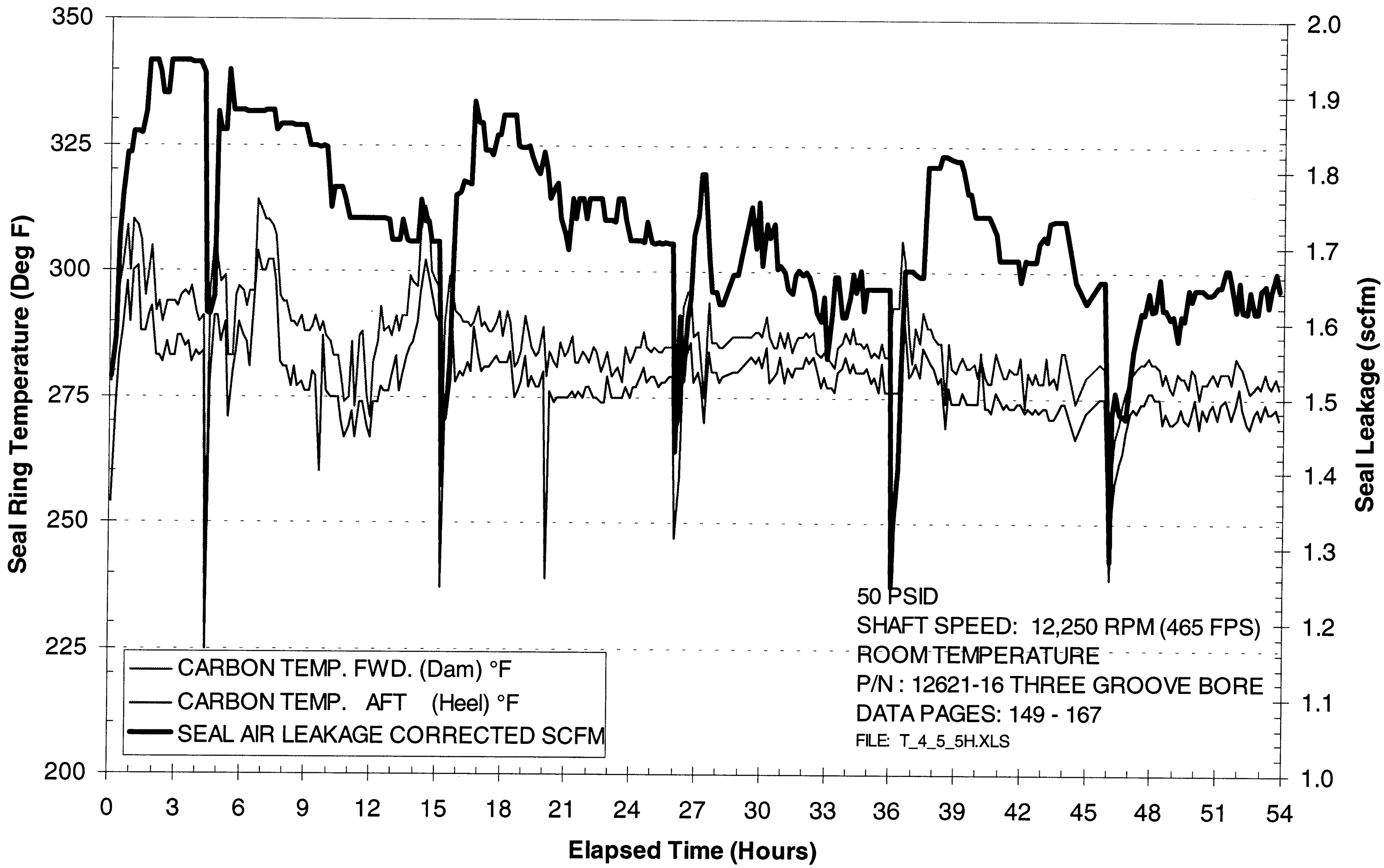
Seal Leakage vs. Pressure Differential



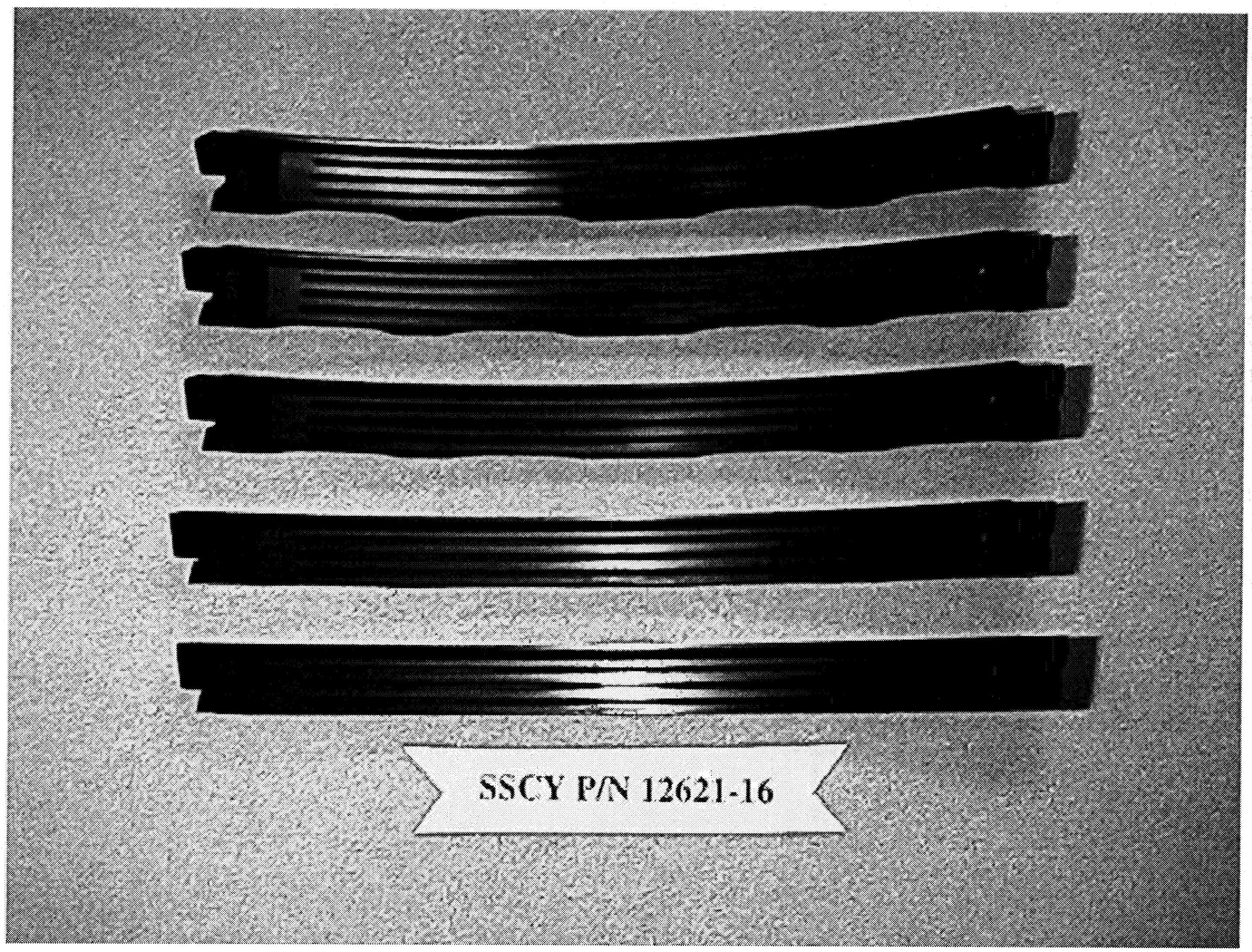


Dynamic Test Results - Endurance Test

TIME vs. SEAL RING TEMP. AND SEAL LEAKAGE
HIGH PRESSURE HYDRODYNAMIC CIRCUMFERENTIAL SEAL



Hydrodynamic Gas Seal Photo



Hydrodynamic Gas Seal
Test Results - Wear Life Summary

Test Condition	Seal Type	
	Hydrodynamic (Gas)	Hydrodynamic (Steam)
Shaft Speed (rpm)	13,350	3,600
PLV (ft/sec)	510	188
ΔP (psid)	50	20
ΔT (Deg F)	450	500
Elasped Time (hours)	160	174
Estimated Life (hours)	**>40,000**	**30,250**

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Hydrodynamic Circumferential Seals
Oil Seals
Program Goals

- Control Oil Leakage at Varied Pressures
- Seal Bearing Oil in Generators
  - Replace Generator Gland Seals
- Provide Long Seal Life (> 50,000 hours)
- Provide Gas Sealing during “Failure” Mode

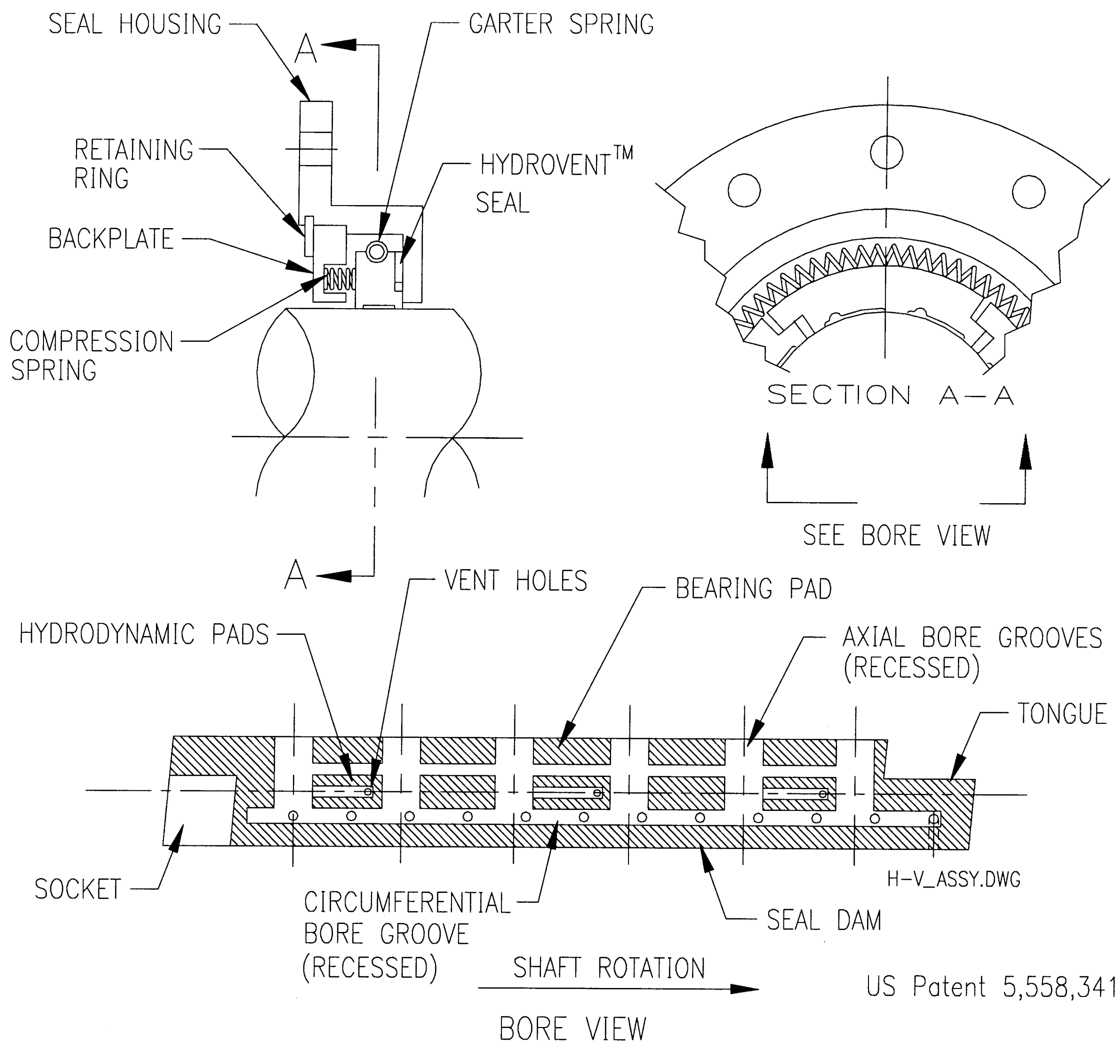
Hydrodynamic Circumferential Seals
Oil Seals
Operating Conditions

Hydrovent™* Seal

– Shaft Speed: 365 ft./sec.
– Press. Diff.: <85 psid
– Oil Temp.: 120 °F
– Leakage: Controlled (< 30 gal/hr)
– Seal Life: 50,000 hours

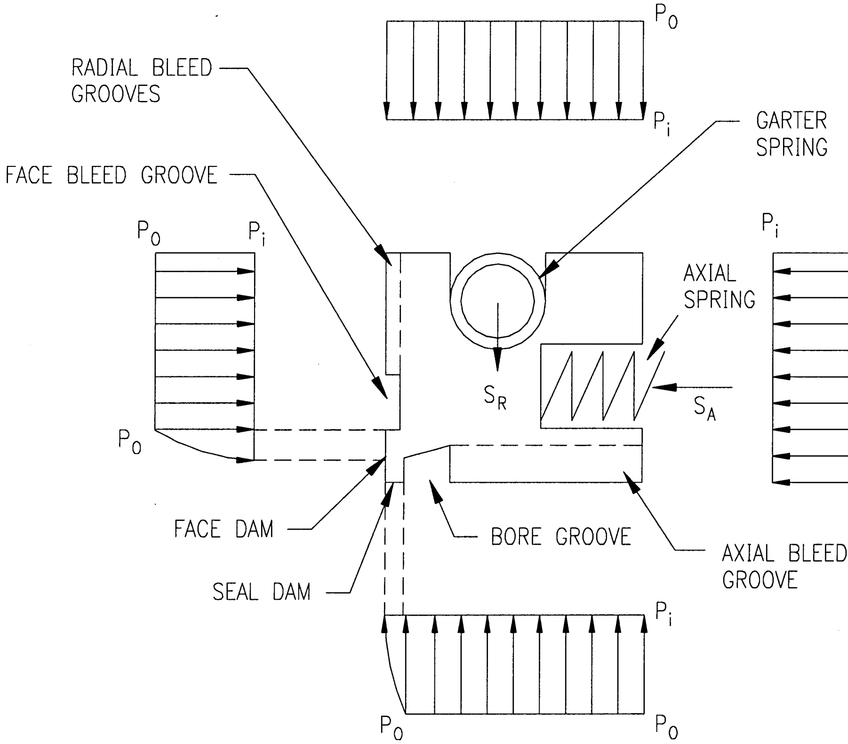
* A trademark of the Stein Seal Company, Kulpsville, PA
US Patent # 5,558,341

Hydrovent™ Oil Seal



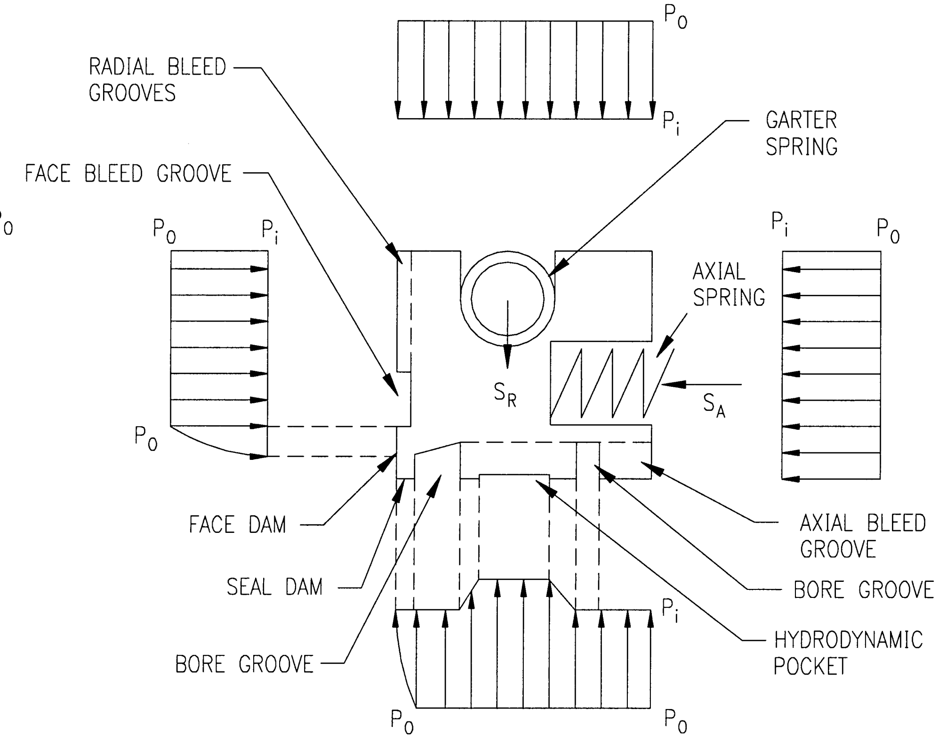
HYDROVENT™ SEAL WITH LIFT POCKETS

Force Diagrams
Oil Seals



P_O = PRESSURE, UPSTREAM
P_i = PRESSURE, DOWNSTREAM
S_A = SPRING LOAD, AXIAL
S_R = SPRING LOAD, RADIAL

FORCE DIAGRAM
CIRCUMFERENTIAL SEAL

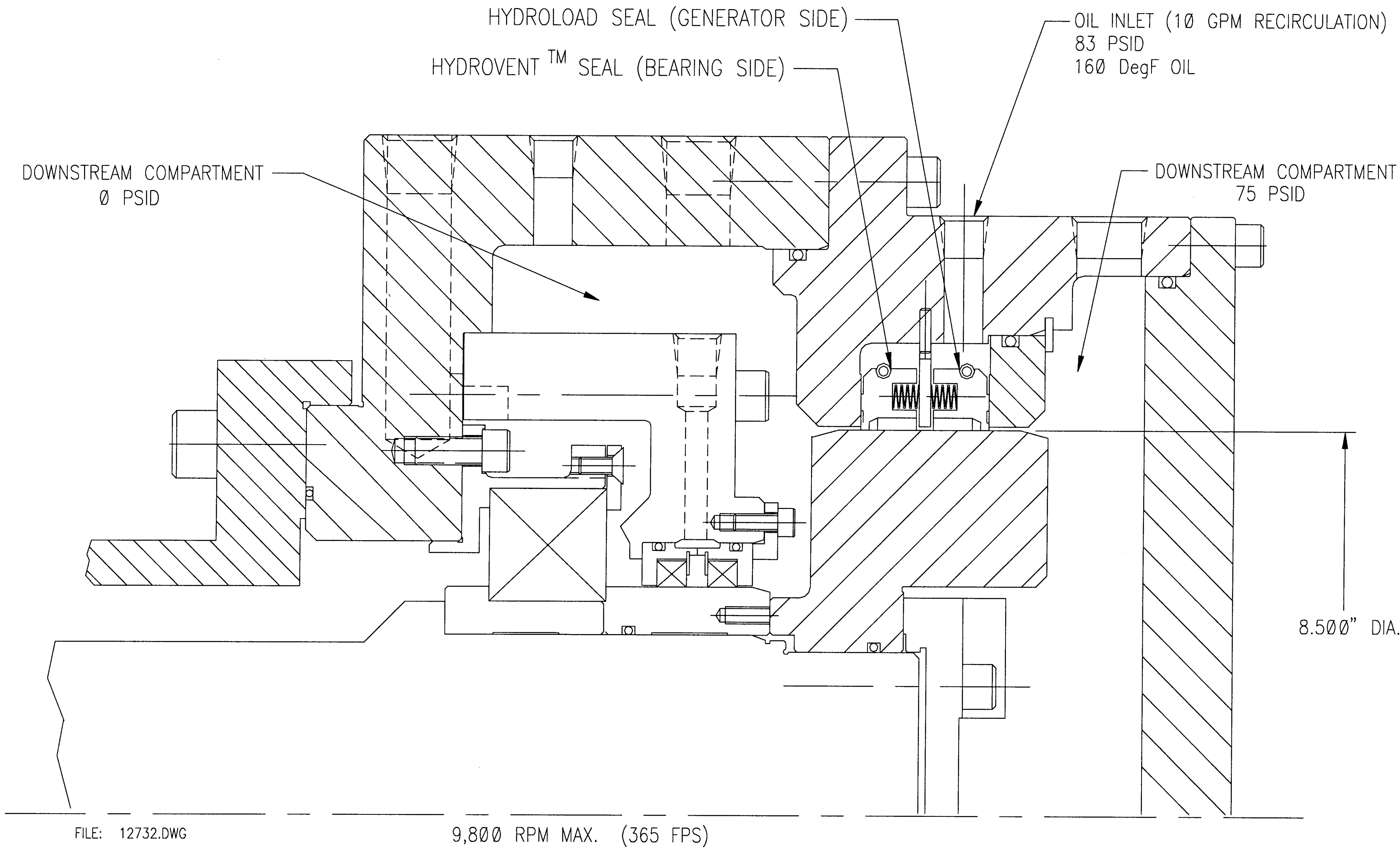


P_O = PRESSURE, UPSTREAM
P_i = PRESSURE, DOWNSTREAM
S_A = SPRING LOAD, AXIAL
S_R = SPRING LOAD, RADIAL

FORCE DIAGRAM
HYDROVENT™ CIRCUMFERENTIAL SEAL

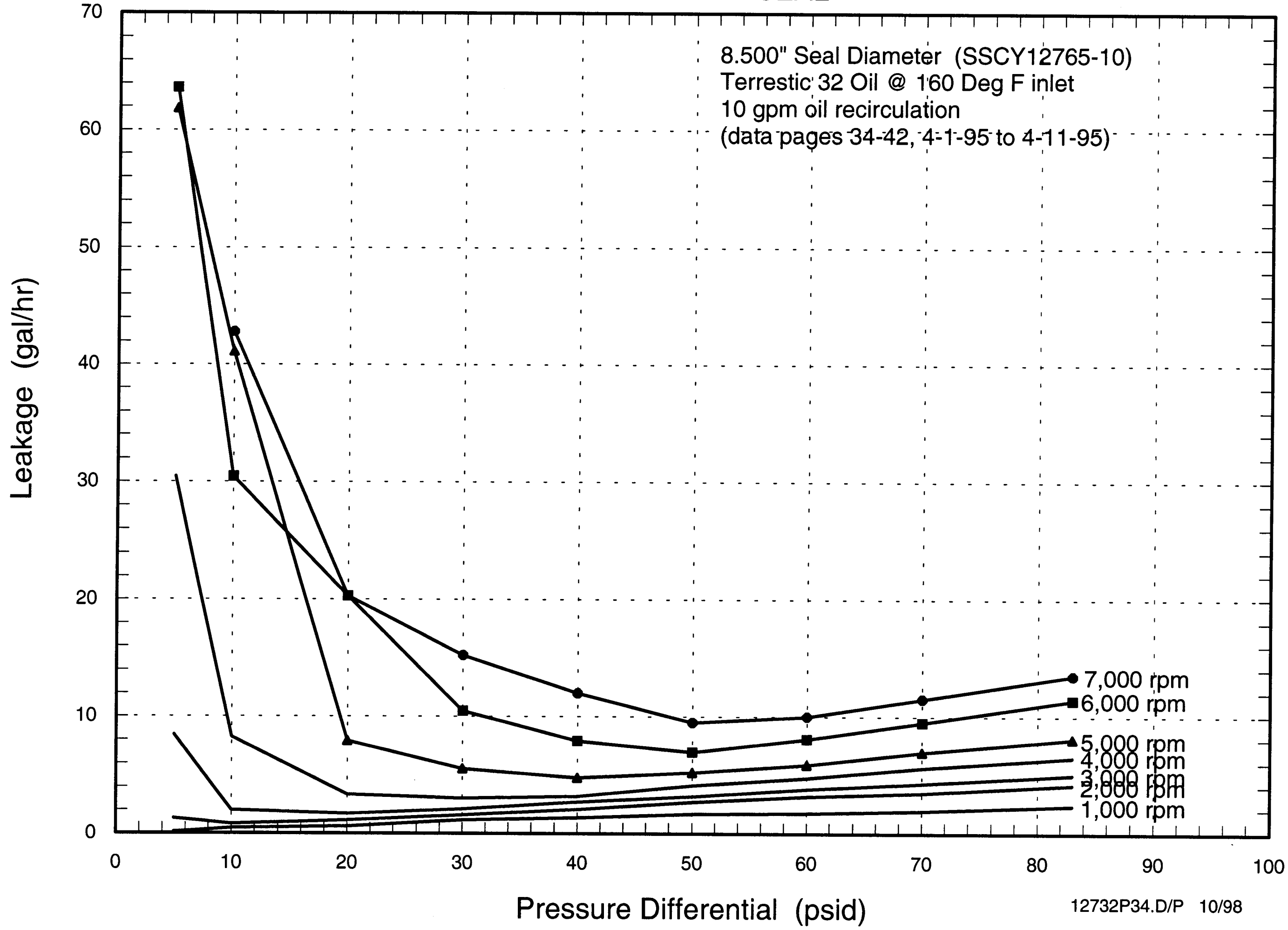
Hydrovent™ Seal Photograph

Hydrodynamic Oil Seal
Dynamic Test Rig

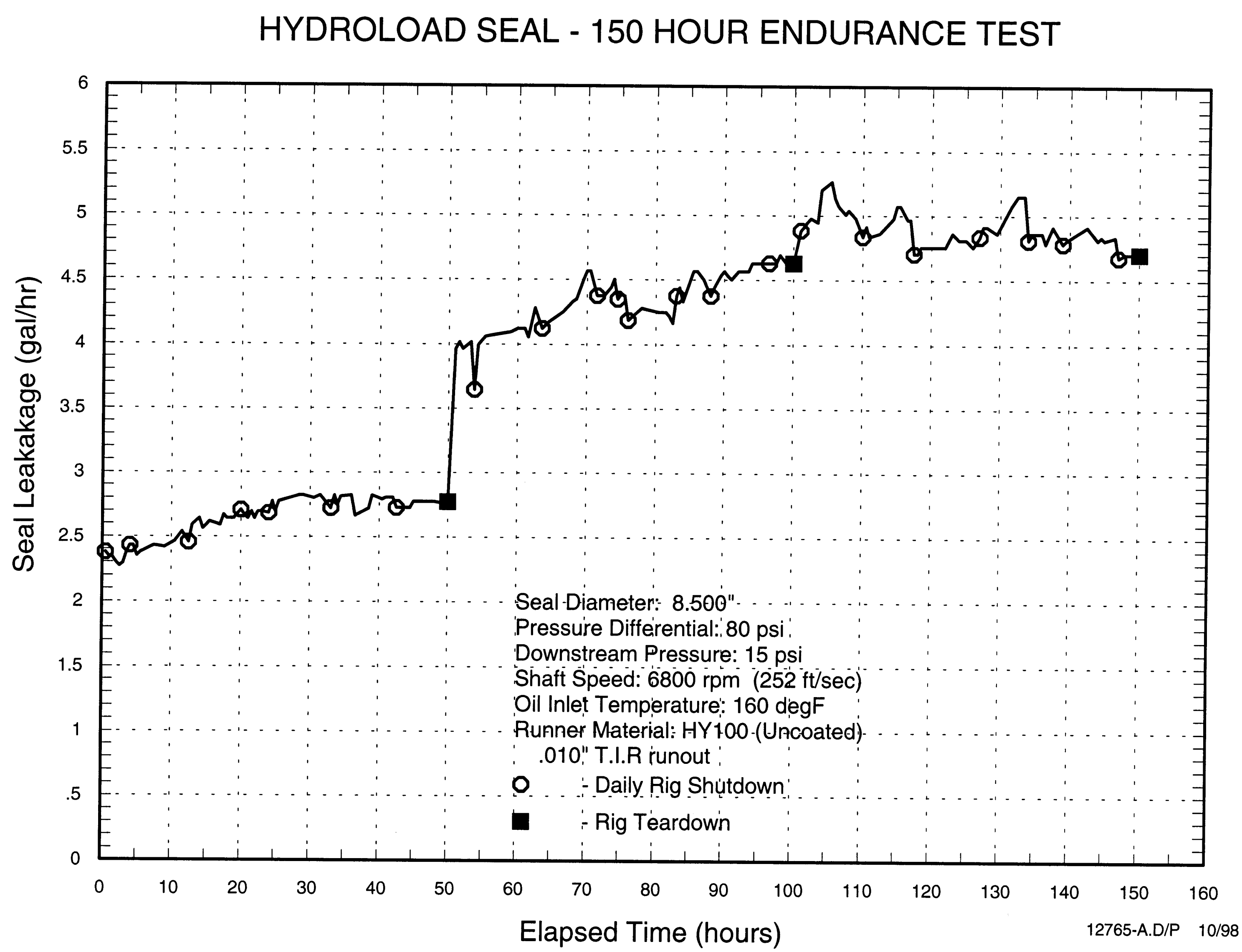


Dynamic Rig Test
Performance Mapping

SEAL LEAKAGE vs. PRESSURE DIFFERENTIAL
HYDROVENT SEAL



Dynamic Rig Test - Endurance Test



Hydrodynamic Oil Seal
Current Conclusions

- Hydrovent™ Seal operated successfully to:
  - 365 ft/sec (goal: attained)
  - 83 psid (goal: attained)
  - 160 °F (goal: 120 °F)
  - Seal leakage: < 30 gal/hr.
  - Seal operated successfully during 150 hr. endurance test with 10 mil rotor swash
- Seal performance is predictable
  - Stein computer codes & validation tests agree
  - Further code development is ongoing
- Additional tests are required & ongoing

Hydrostatic Face Seal Development

- Aspirating Face Seal
  - Compressor Discharge
- Stepped Face Seal
  - Turbine Rim Sealing
  - Compressor Discharge

Aspirating Seal Improvement

Funding:

- Provided by GEAE
  - Cincinnati, OH
- Developed under NASA's AST program
  - Lewis Research Center

Program Goals:

- Increase gas film stiffness compared to existing seal
  - (1994 design)
- Maintain gas film clearance
  - .0015″ to .0025″
- Maintain rotor runout capability at:
  - .005″ & .010″
- Build & rig test sub-scale seal
- Build full size seal & rig test at GE CRD

Aspirating Seal Improvement

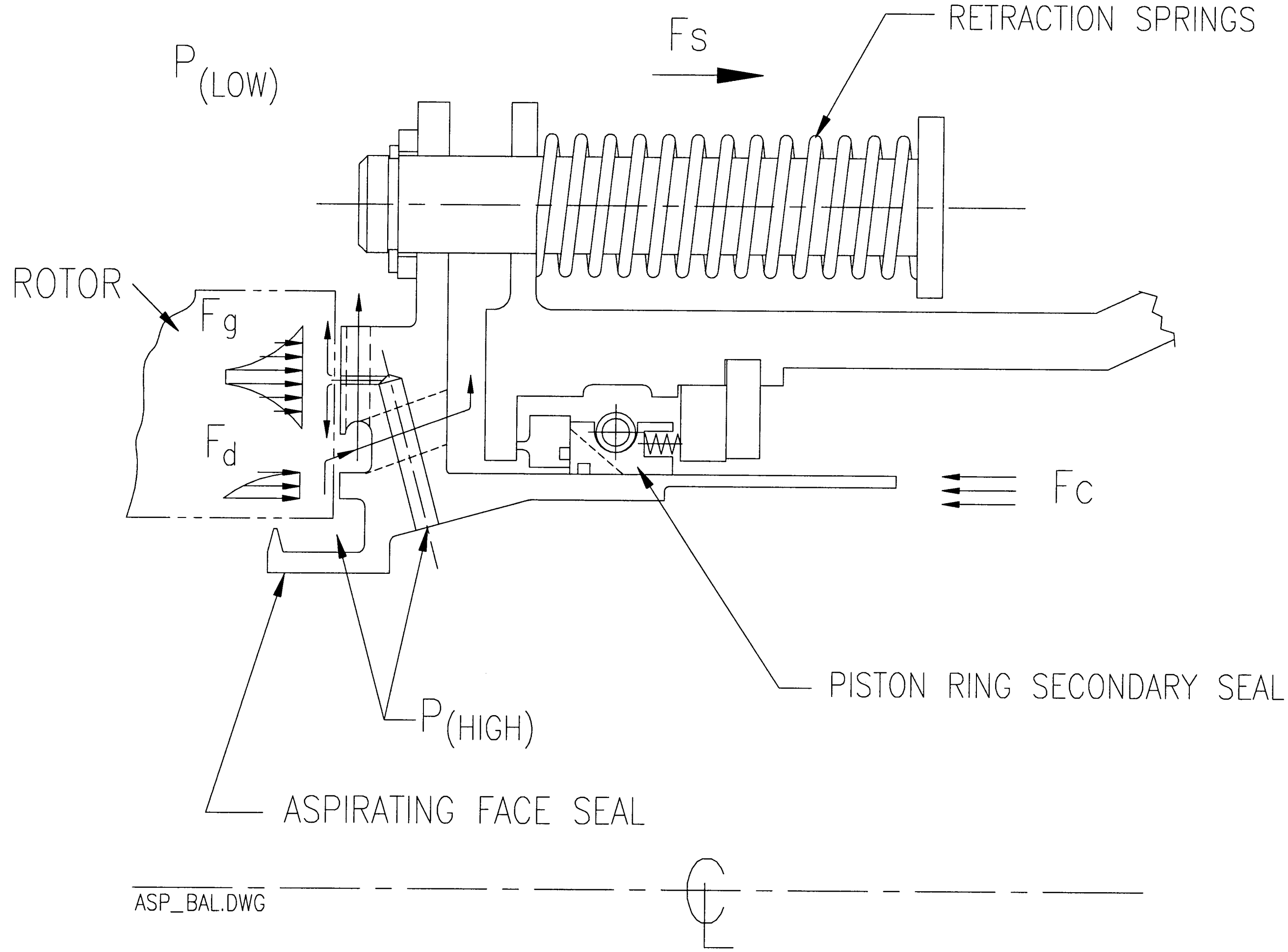
Two seal sizes developed

- 36″ seal (GE-90)
  - For rig testing at GE CR & D
  - Design utilizes existing rig rotor with modifications
- 14.7″ seal (sub-scale)
  - Optimized design
  - For rig testing at Stein

Aspirating Seal

ASPIRATING SEAL FORCE BALANCE

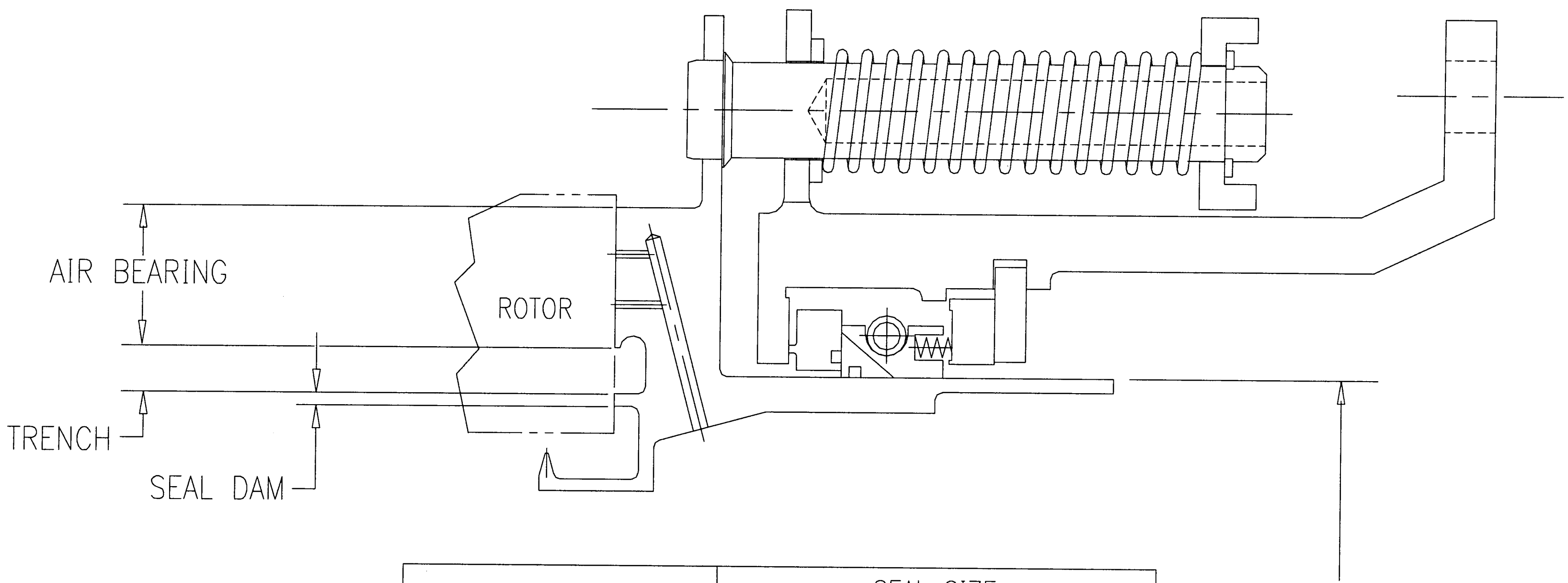
FORCE BALANCE EQUATION: $Fc = Fg + Fd + Fs + Inertia + Friction$



Aspirating Seal - Work Performed

- Parametric studies
  - Varied seal dam, gas bearing features, & trench geometry's to determine performance effects
- Optimized design
  - 36″ seal, .550″ gas bearing, .050″ dam, .180″trench
    - » Rotor flow deflector required
  - 14.7″ seal, 1.250″ gas bearing, .250″ dam, .450″ trench
    - » Eliminated need for rotor flow deflector
- CFD analysis (CFDRC Corp.)
  - Performed on 14.7″ & 36″ seals
  - Operating gap: .0015″ to .0020″
- Gas bearing rig tests
  - Validation of analytical work
    - » NASA's GFACE Code

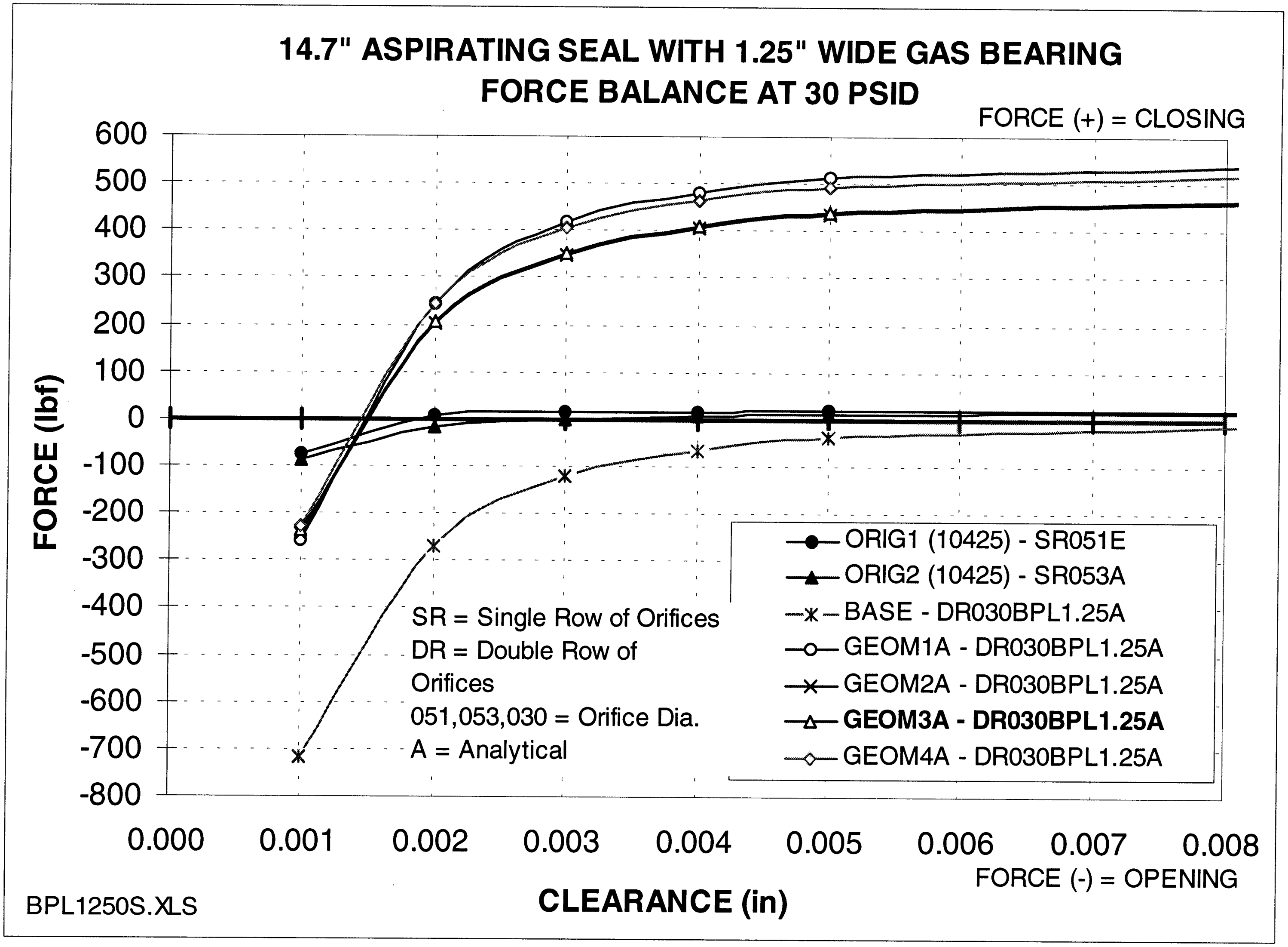
Aspirating Seal Dimensions



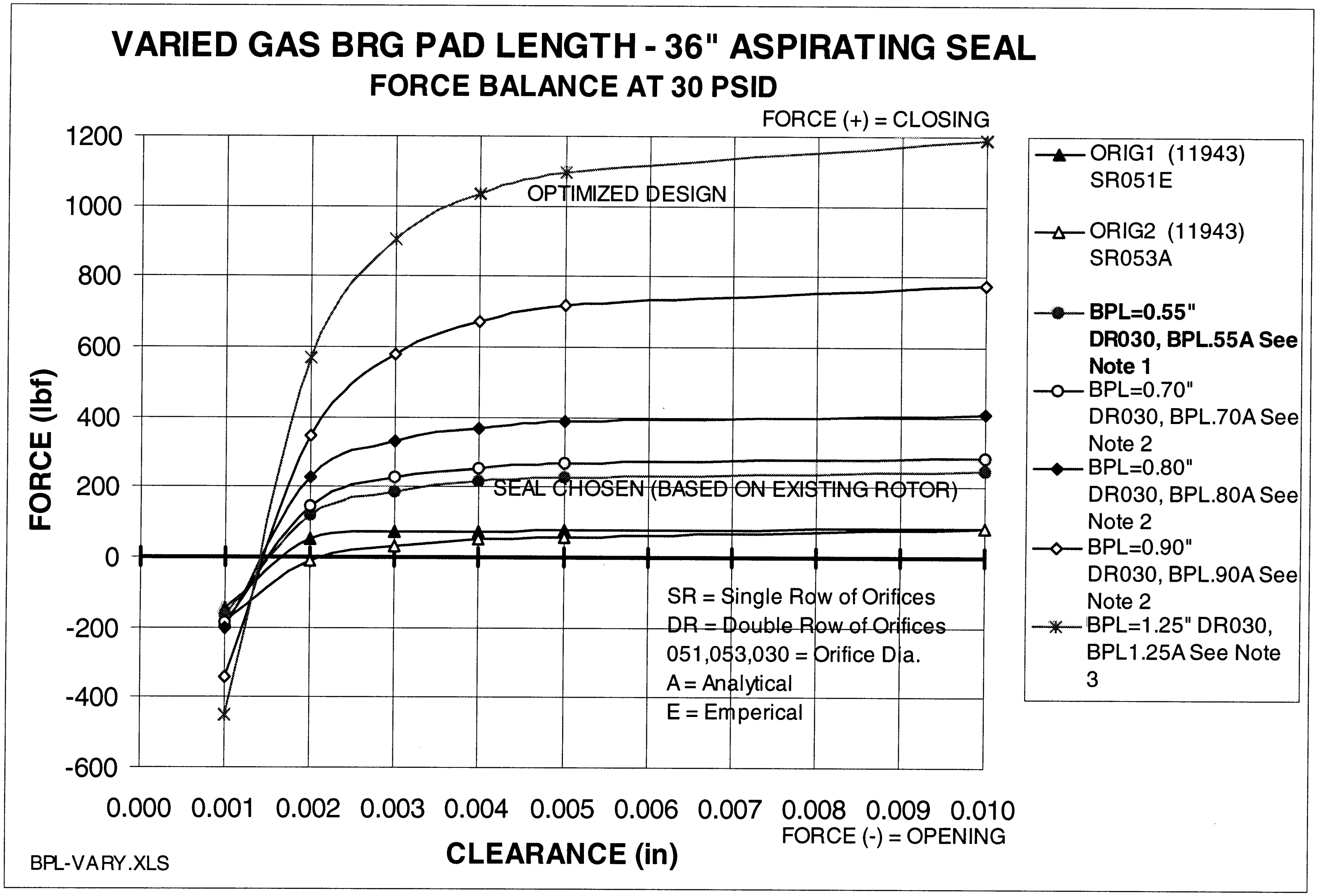
DIMENSION	SEAL SIZE	
	14.7"	36"
AIR BEARING WIDTH	1.250"	.550"
TRENCH	.450	.180"
SEAL DAM	.250"	.050"
BALANCE DIAMETER	14.700"	36.160"
ORIFICE DIA	.030"	.030"
ORIFICE SPACING	.828"	.806"
NUMBER OF ROWS	2	2

ASP_14-36.DWG

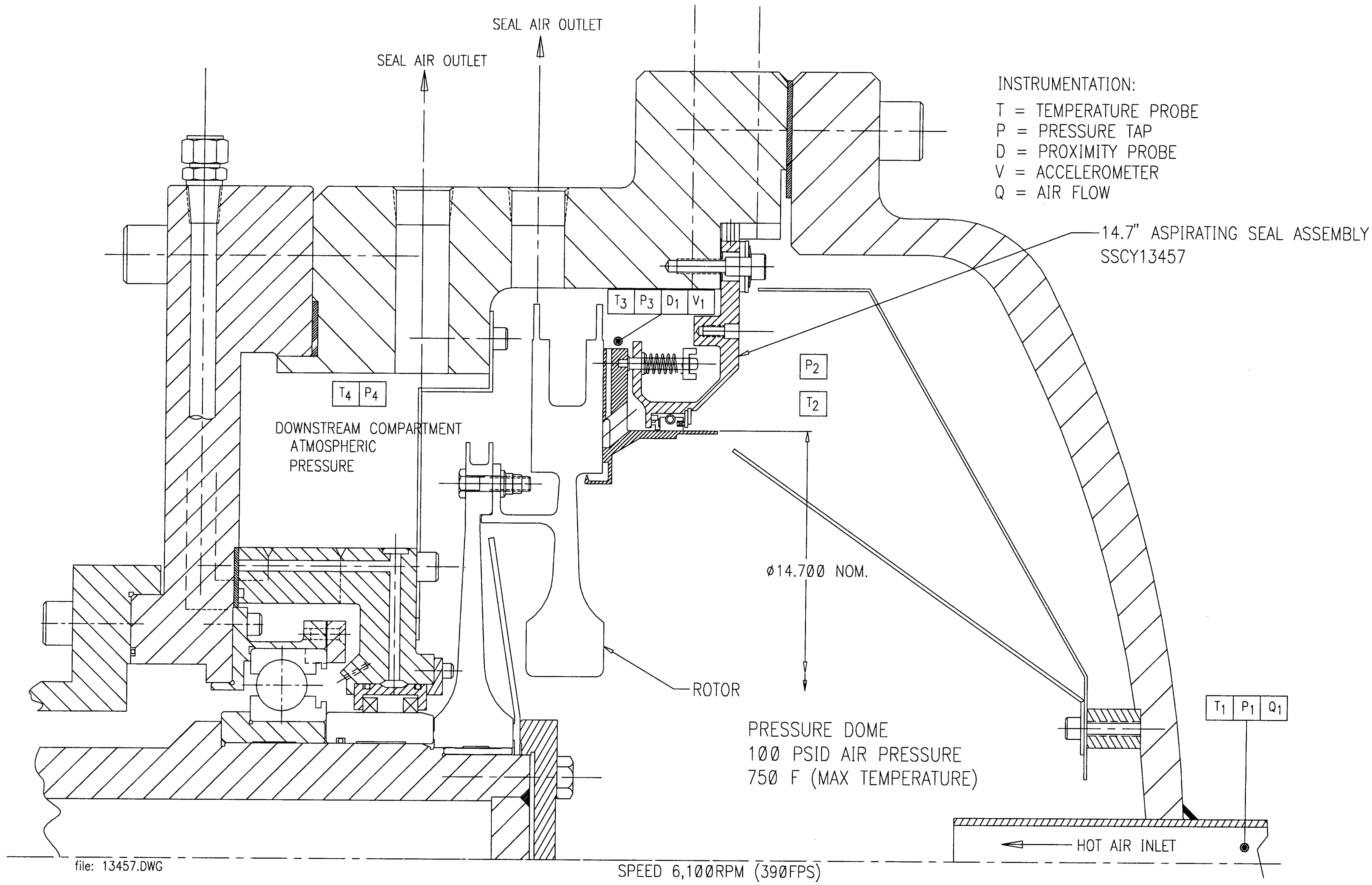
Aspirating Seal Development
Force vs. Clearance - 14.7″ seal



Aspirating Seal Development
Force vs. Clearance - 36″ seal



14.7" Aspirating Seal - Dynamic Test Rig



Stepped Face Seal Development

Program Goal:

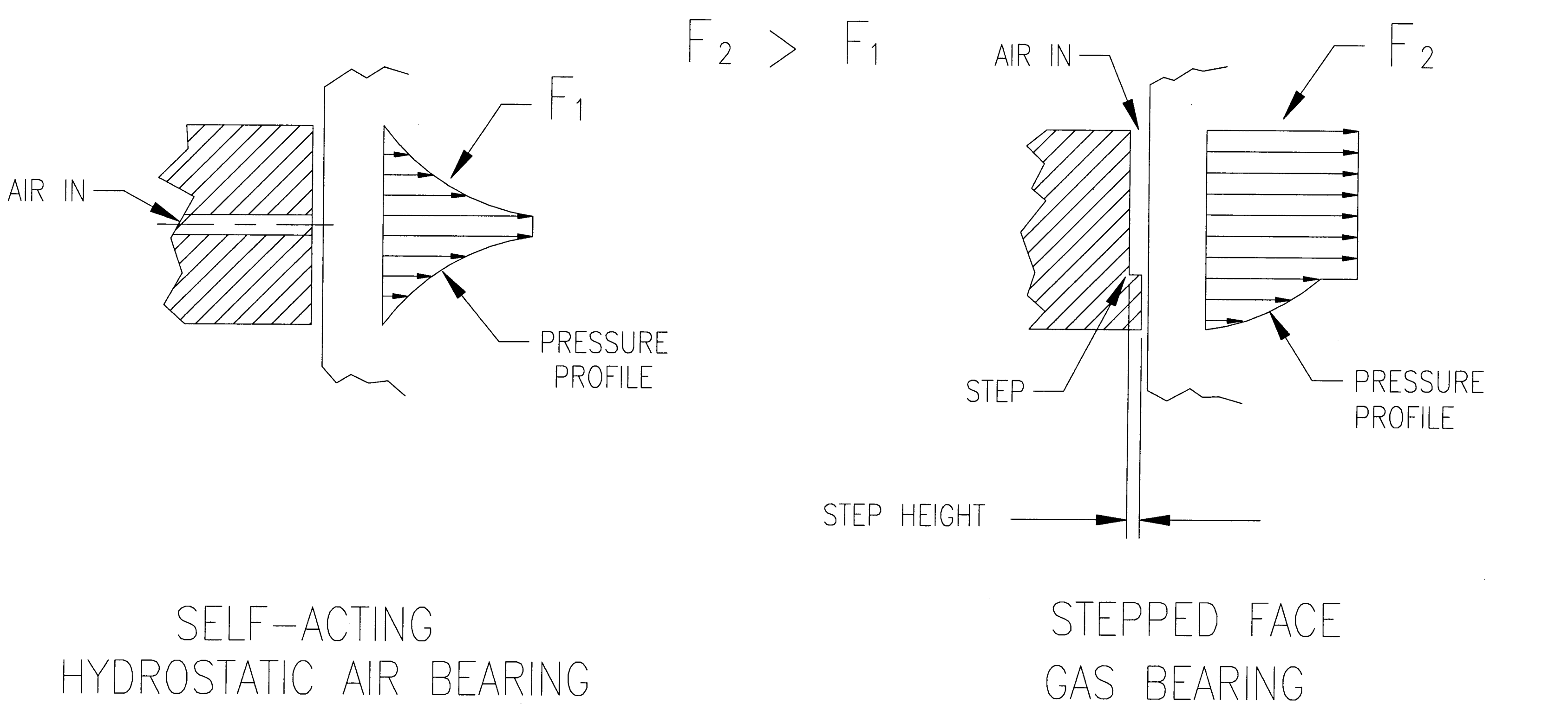
- Develop seal for:
  - High temp. & press.
  - Low leakage
  - All metal seal design
- Hydrostatic Seal
  - Stepped face gas bearing
  - Non-Contacting
    - ~.0015″ film clearance
- US Patent pending

Conditions:

- Temperature: ~ 1300 ^oF
- Speed: 1,050 ft/sec
- Pressure: > 250 psid
- Applications:
  - Turbine Rim Seal
  - Compressor Discharge

Stepped Face Seal Development

HYDROSTATIC GAS BEARING vs. STEPPED FACE GAS BEARING

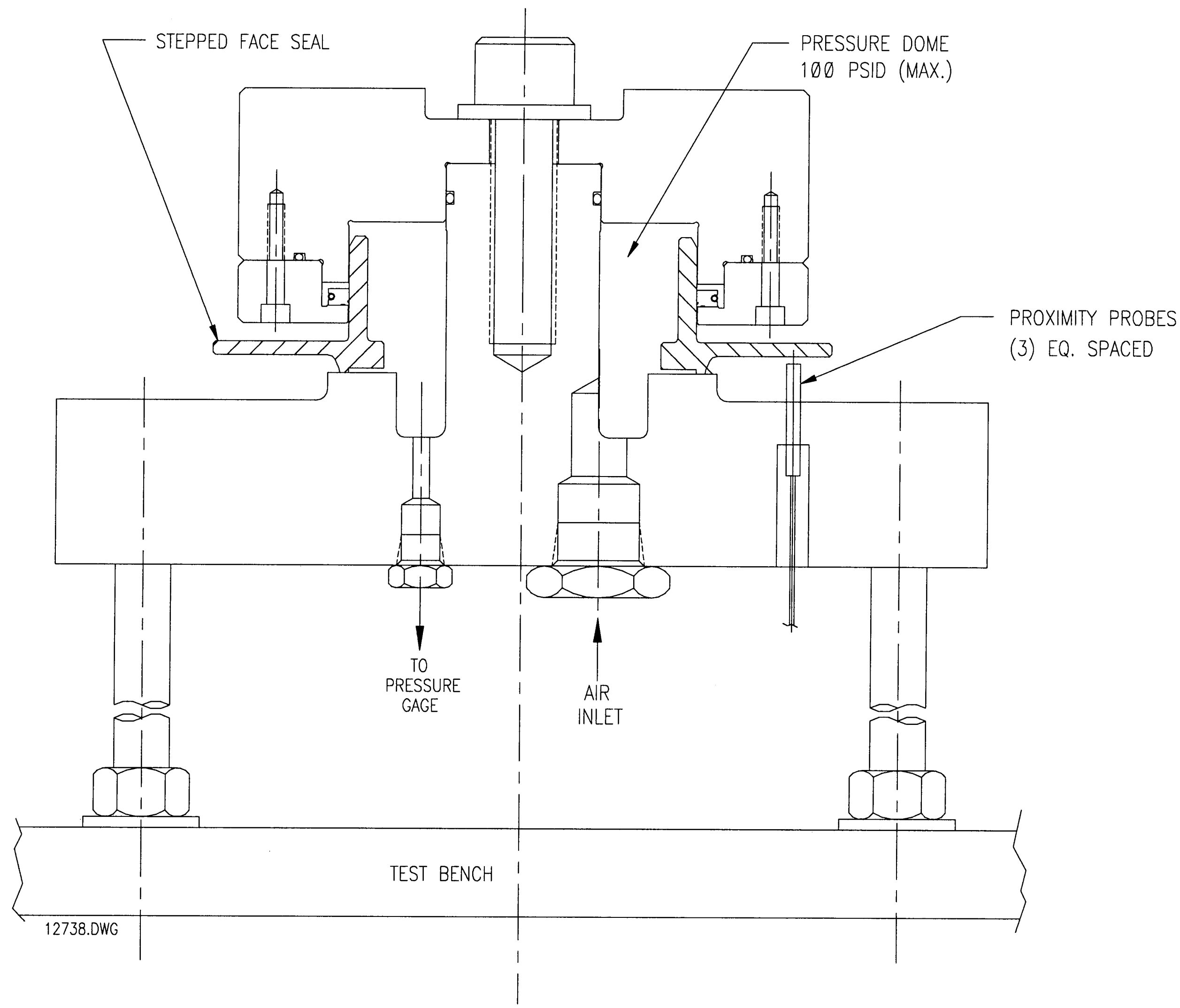


12920FIG.DWG

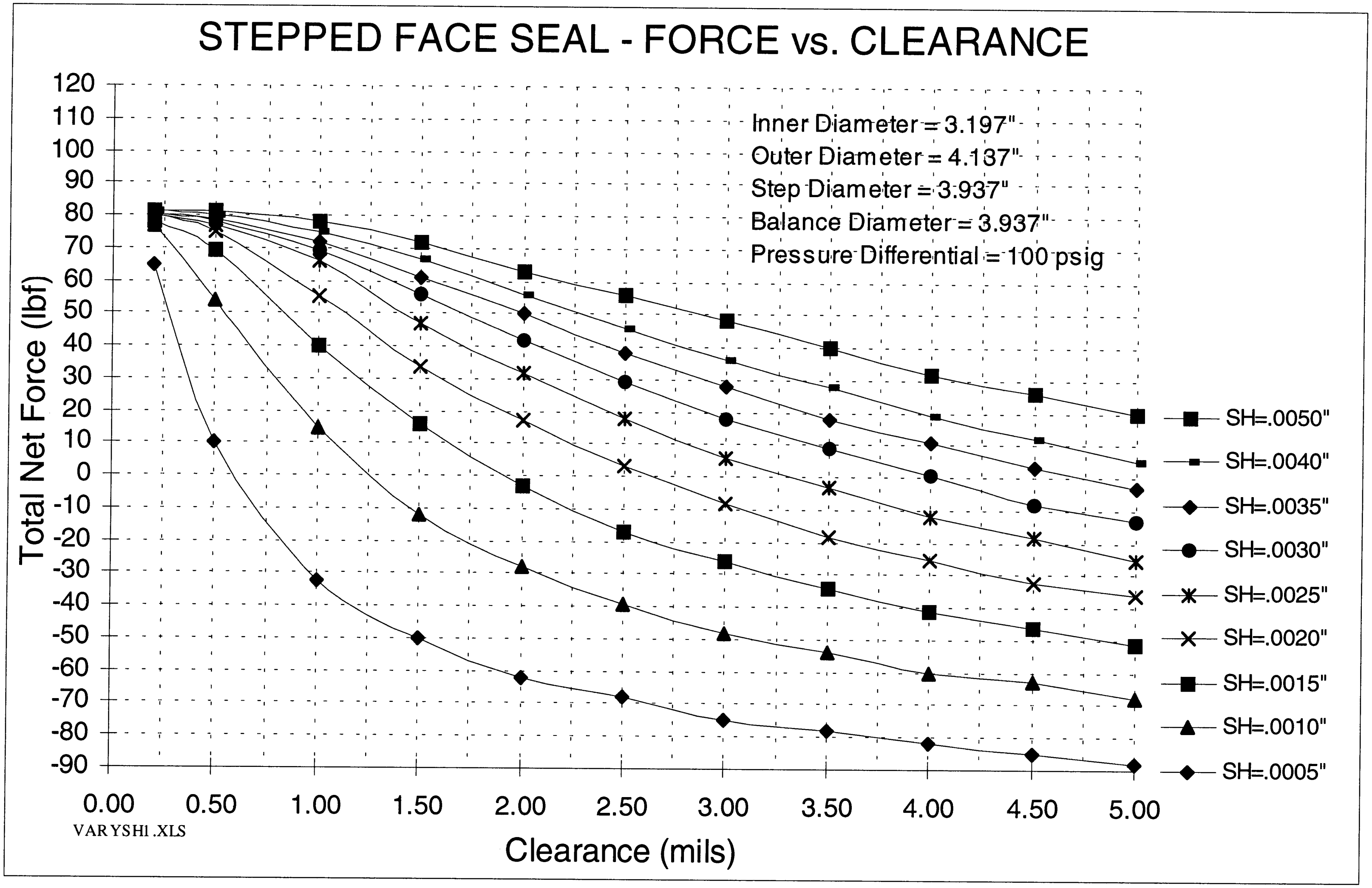
Stepped Face Seal
Computer Code Development

- Code 1
  - Evaluates *hydrostatics* of the seal interface
    - » Calculates pressures, forces, & flow
  - Uses compressible laminar & turbulent flow analysis
  - Includes effects of taper on rotor, seal step face, & dam
- Code 2
  - Calculates *dynamic response* of seal system due to rotor swash.
  - Includes hydrostatic forces, inertia forces, friction forces for secondary seal & anti-rotational locks
  - Uses Code 1 as sub-routine
  - Seal FEA results as input into Code 2.

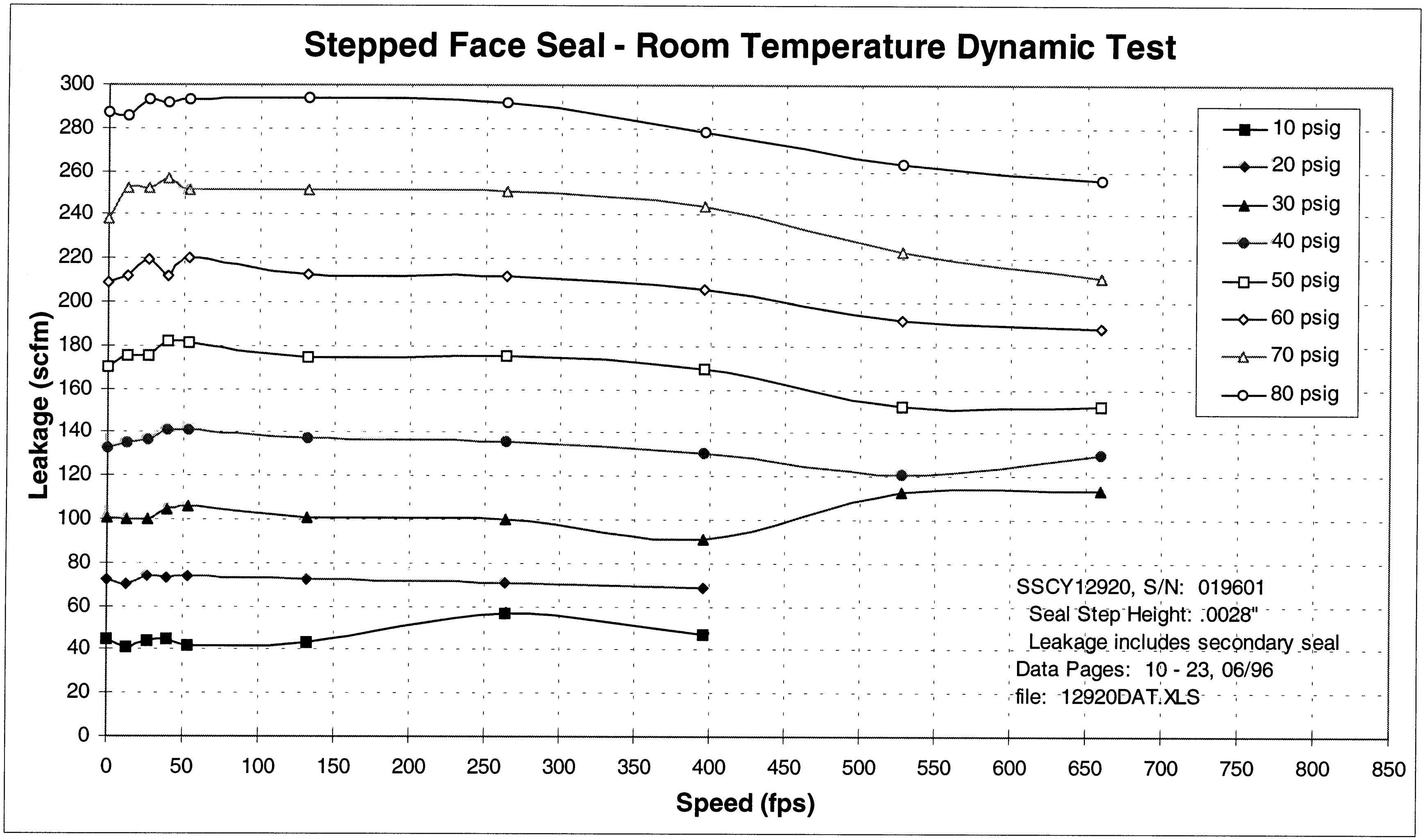
Sub-scale Static Test Rig
Stepped Face Seal



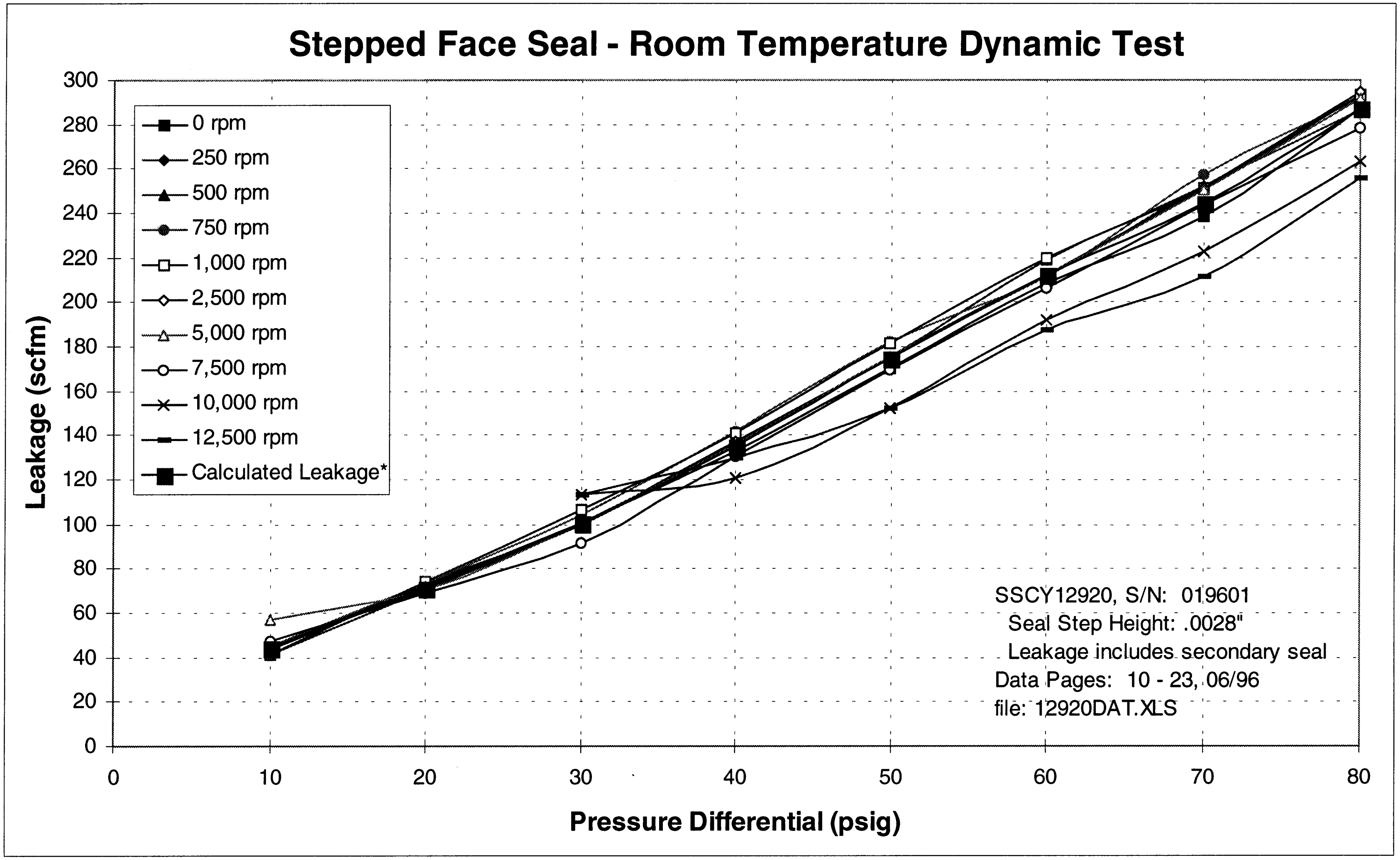
Stepped Face Seal
Effects of Step Height



Dynamic Test Results
Leakage vs. Speed



Dynamic Test Results
Leakage vs. Pressure



Stepped Face Seal - Current Conclusions

- Seal operated successfully to:
  - 885 ft/sec (goal: 1050 ft/sec)
  - 100 psid* (goal: 250 psid)
  - 1000 °F (goal: 1300 °F)
  - 3.0 mil rotor swash
- Seal performance is predictable
  - Stein computer codes & validation tests agree
  - CFD analysis correlates computer codes & test data
  - NASA GFACE code correlates seal interface performance & provided additional information
- Additional tests are required & ongoing

*limited by compressor capability

Hydrostatic Intershaft Face Seal

- Being developed under the Government's SBIR program for:

  Naval Air Warfare Center

  Patuxent River, Maryland
- Contract #N00421-97-C-1228
  - Phase II awarded in July 1997
- Technical Rep. (Navy): Pauline Tarrantini

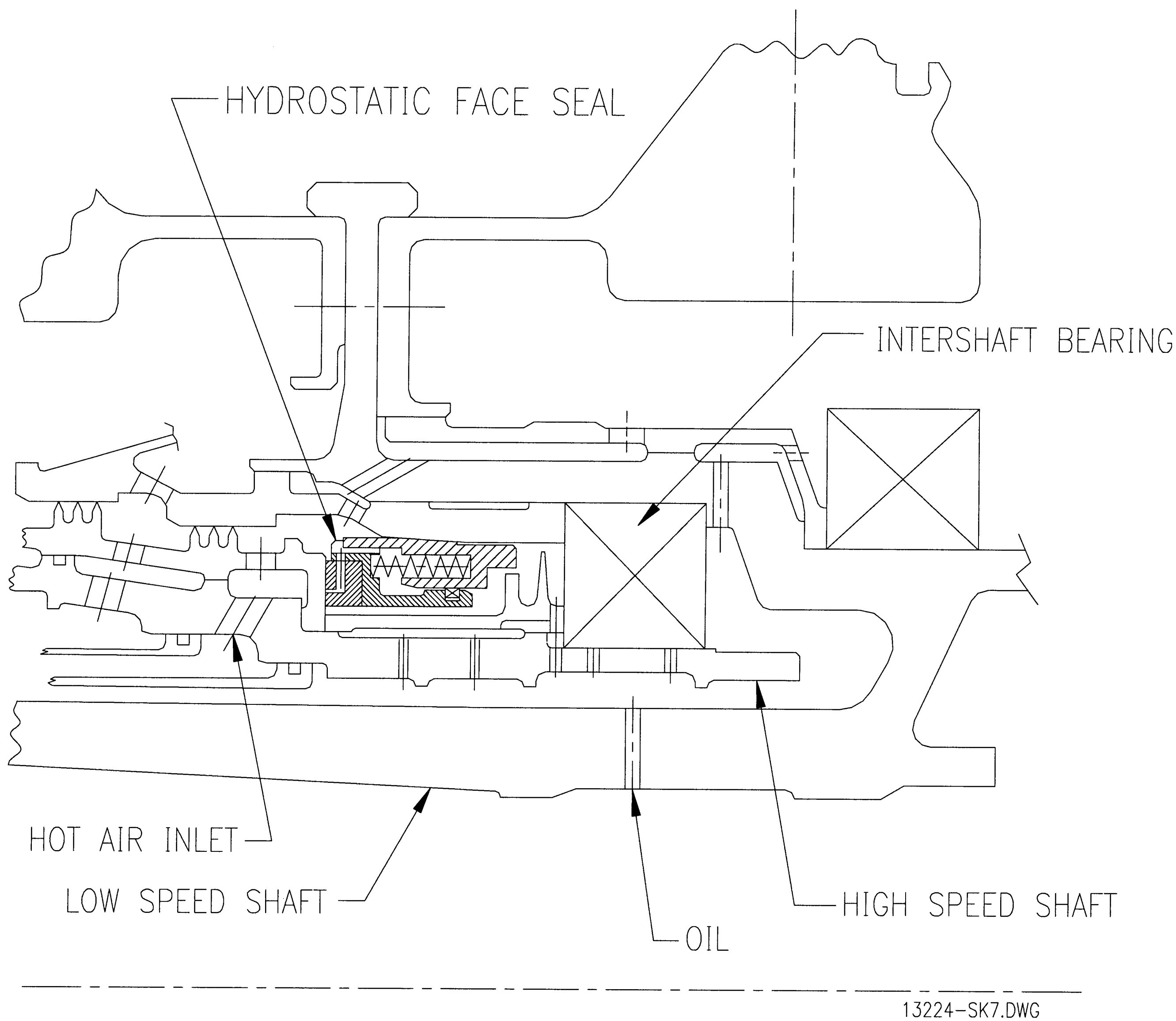
Hydrostatic Intershaft Face Seal
Program Goals

- Produce Seal for IHPTET/JSF Engine
- Meet leakage and performance goals
- Increase Seal Wear Life
- Increase Seal Operating Speed

Hydrostatic Intershaft Face Seal Operating Conditions

- Upstream Pressure 95 psia
- Downstream Pressure 55 psia
- Temperature 850 ^{o}F
- HP Turbine Speed (inner) 18,600 rpm
- LP Turbine Speed (outer) 11,200 rpm
  (Equivalent PLV) 715 fps
- Target Leakage 0.5 SCFM per psid
  (0.11 lbm/sec)
- Seal Diameter ~5.5 "

Hydrostatic Intershaft Face Seal Location

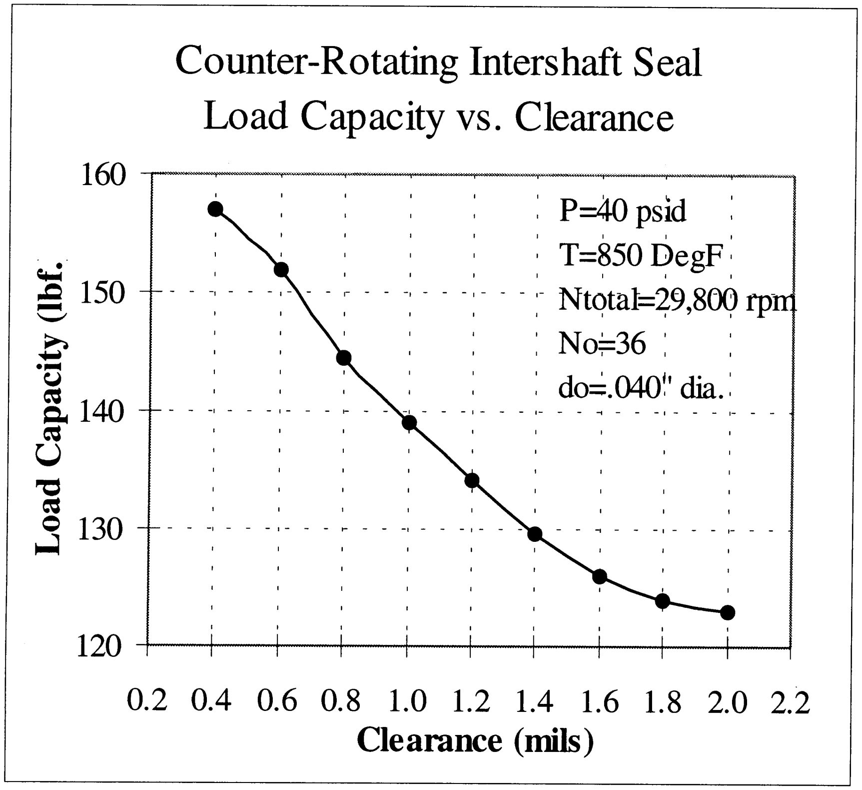


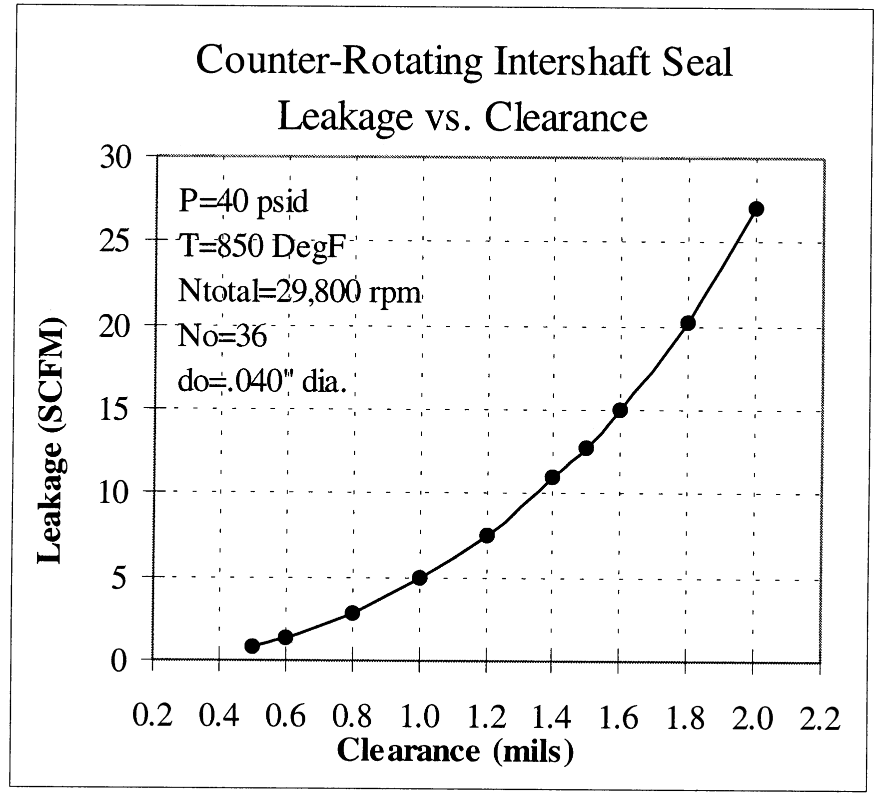
Hydrostatic Intershaft Face Seal

Development Challenge

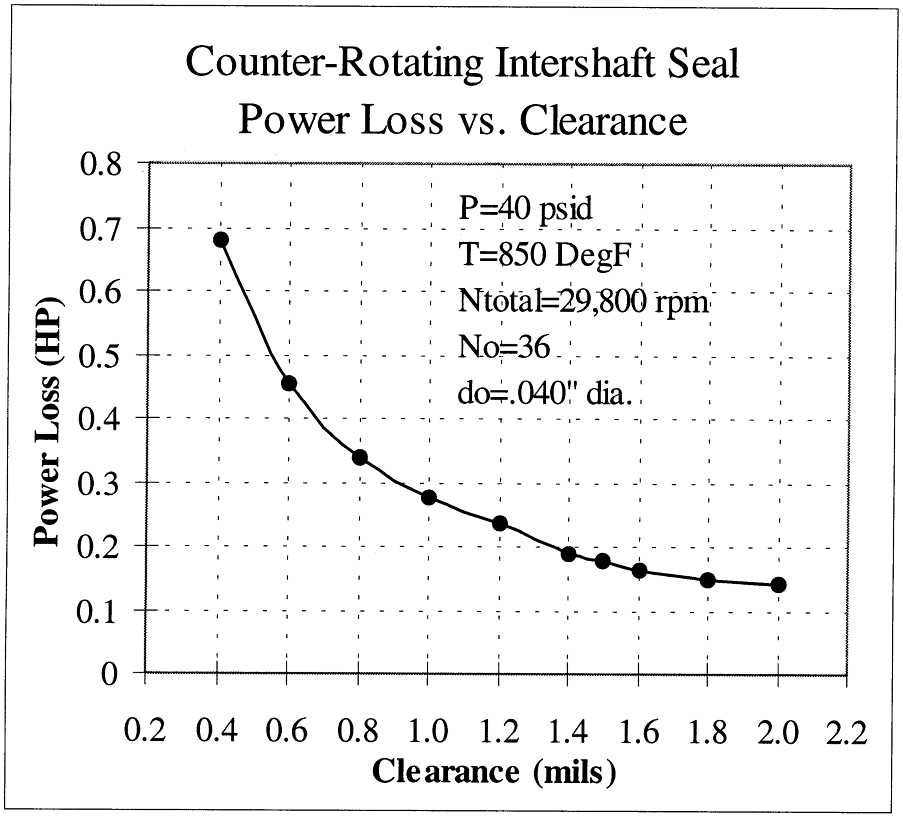
- Dynamic misalignment imposed by the two shafts
- Dynamic excursions of two shafts
- Centrifugal loading on seal
- High interface speeds for seals

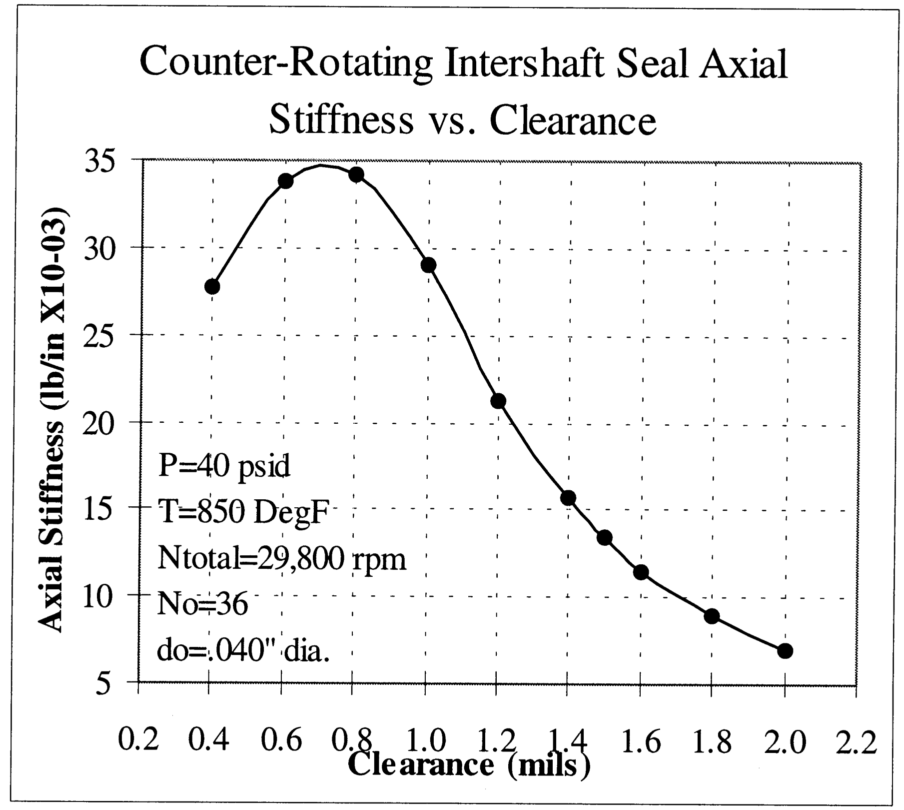
Hydrostatic Intershaft Face Seal
Seal Performance Study



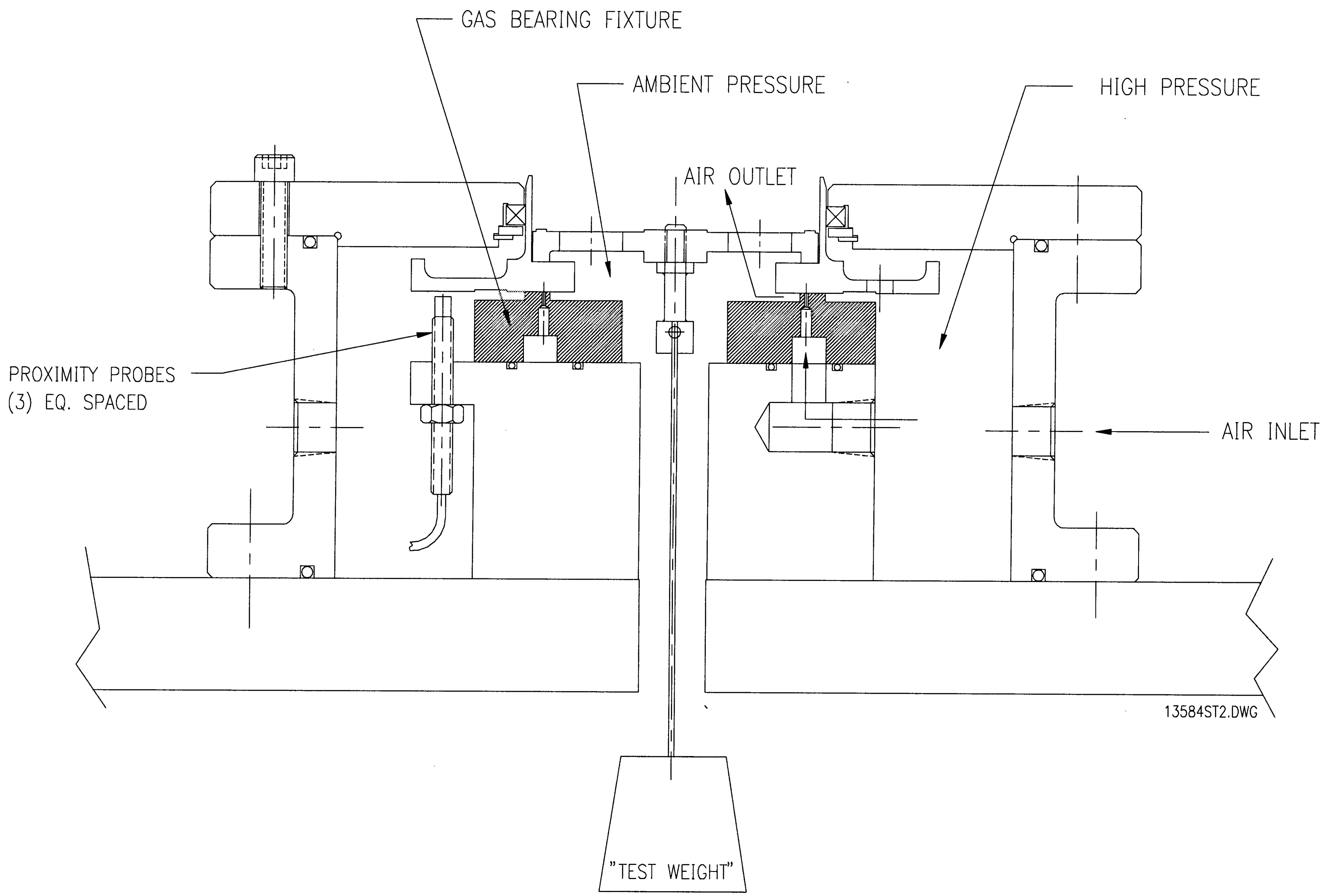


Hydrostatic Intershaft Face Seal
Seal Performance Study





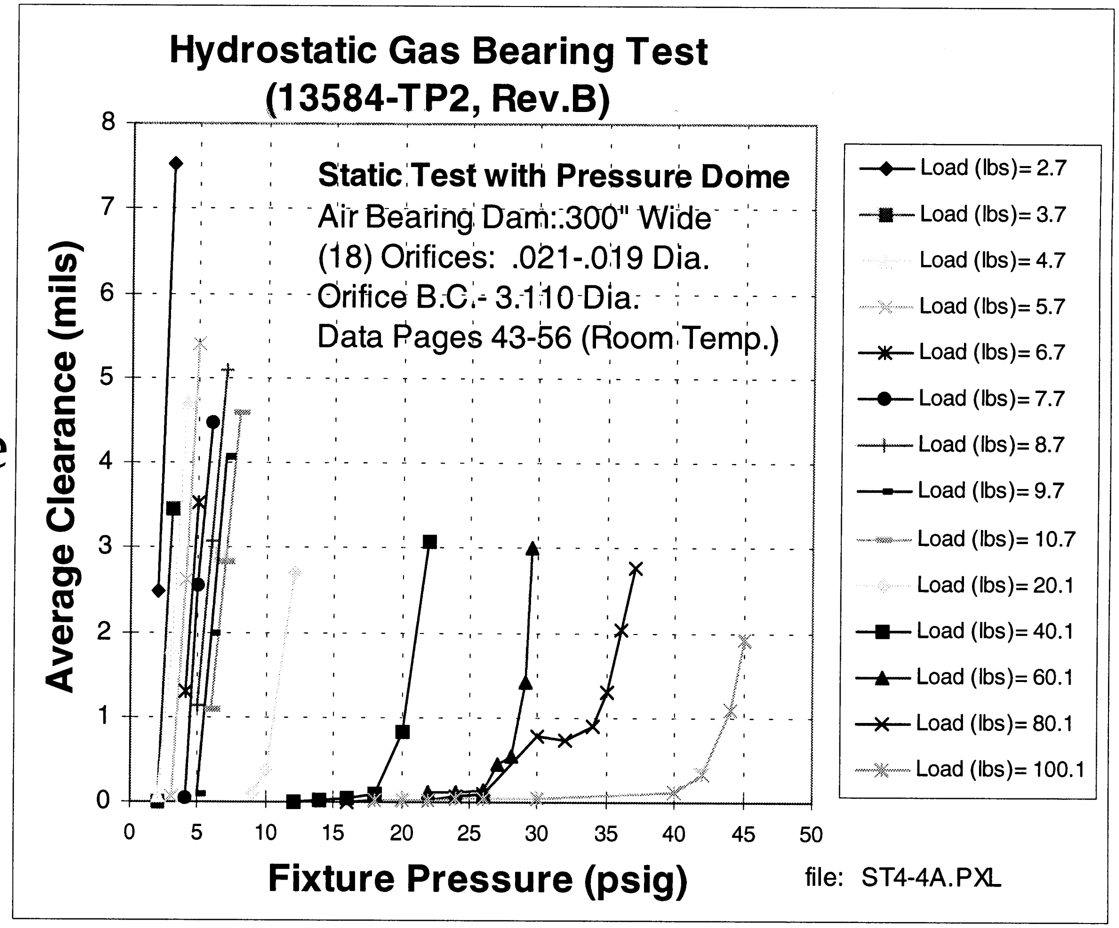
Hydrostatic Intershaft Face Seal
Static Gas Bearing Test Rig



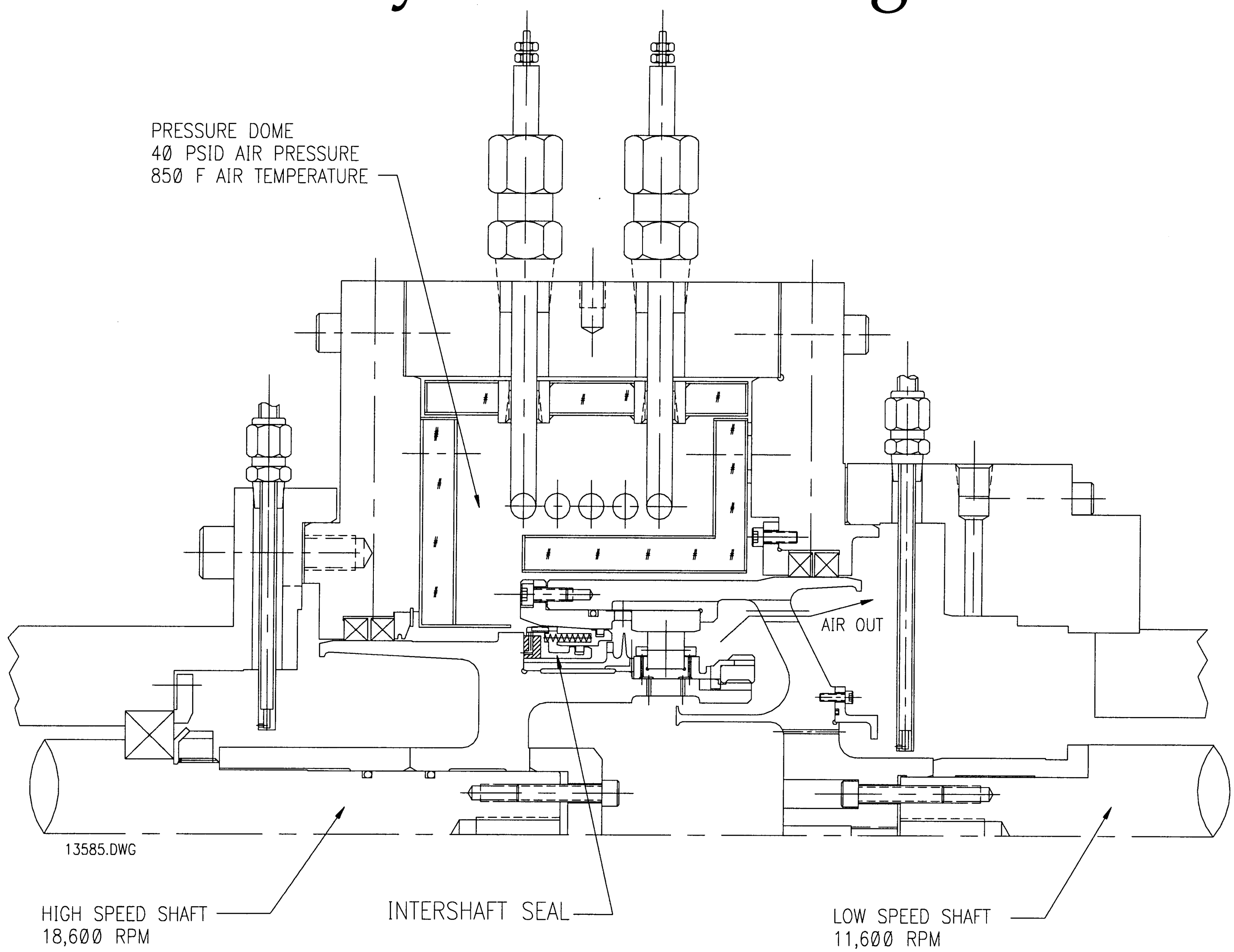
Hydrostatic Intershaft Face Seal
Static Gas Bearing Test Results

Purpose of test

- Validate seal code (GFACE)
- Determine orifice C_d
- Determine performance
  - Leakage vs. Clearance
  - Clearance vs. pressure
  - Recommend seal geometry



Hydrostatic Intershaft Face Seal
Dynamic Test Rig



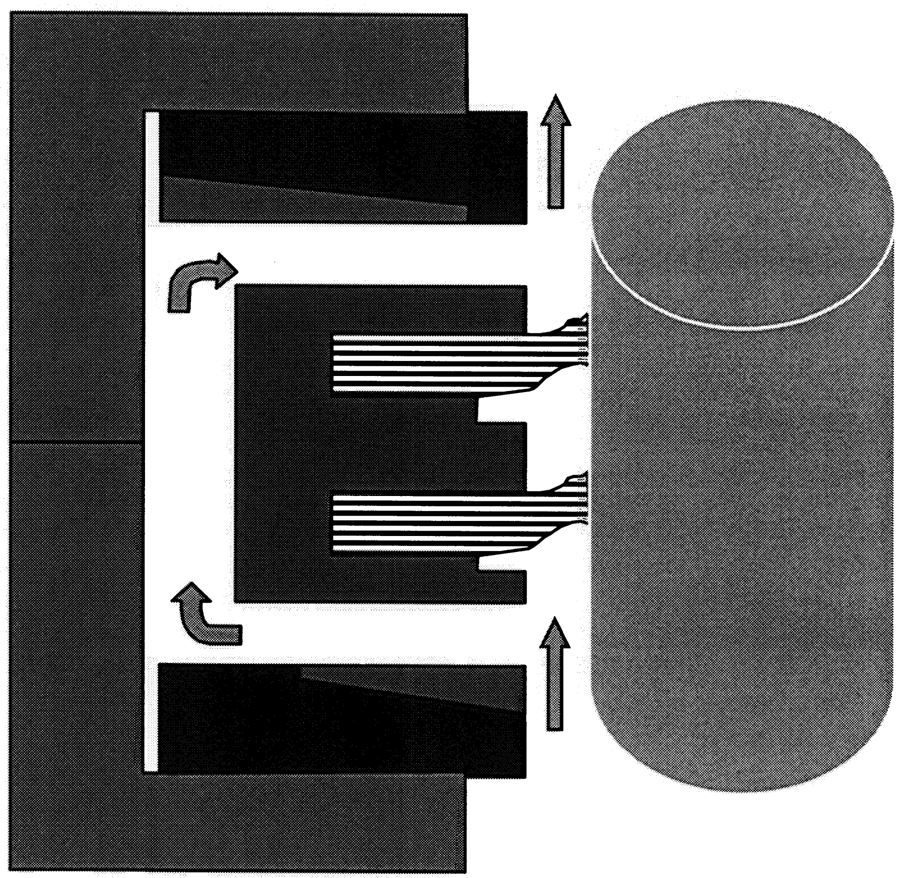
Any Questions or Comments?

FLOWSERVE CORPORATION FLUID SEALING DIVISION

Bill Adams and Tony Artiles
FlowServe Corporation
Kalamazoo, Michigan

Overview

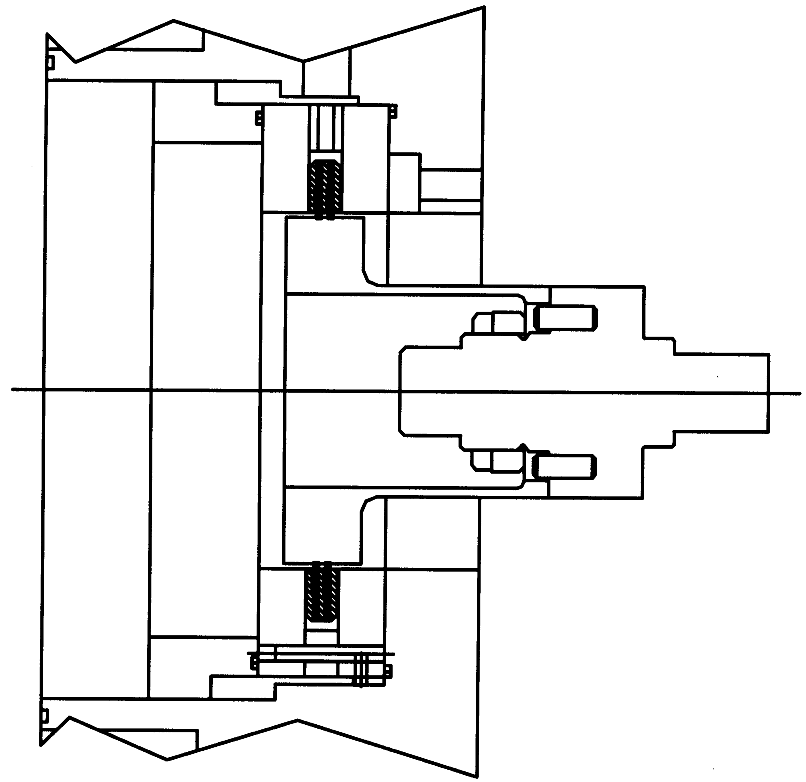
- Company Overview
  - Corporation Structure
  - Merger
  - Fluid Sealing Division
- Seal Developments
- Advanced Hybrid Brush Seal Design
  - Advantages
  - Optimization of Design
  - Performance Summary

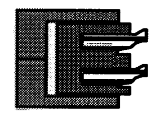


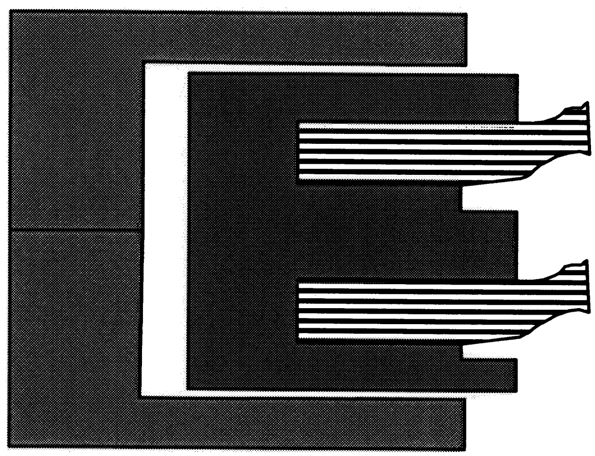
Advantages

- Accommodates large axial shaft motions
- Eliminates:
  - secondary seal hang-up
  - bristle and shaft wear
- Reduced:
  - parts,
  - axial space,
  - cost,
  - energy

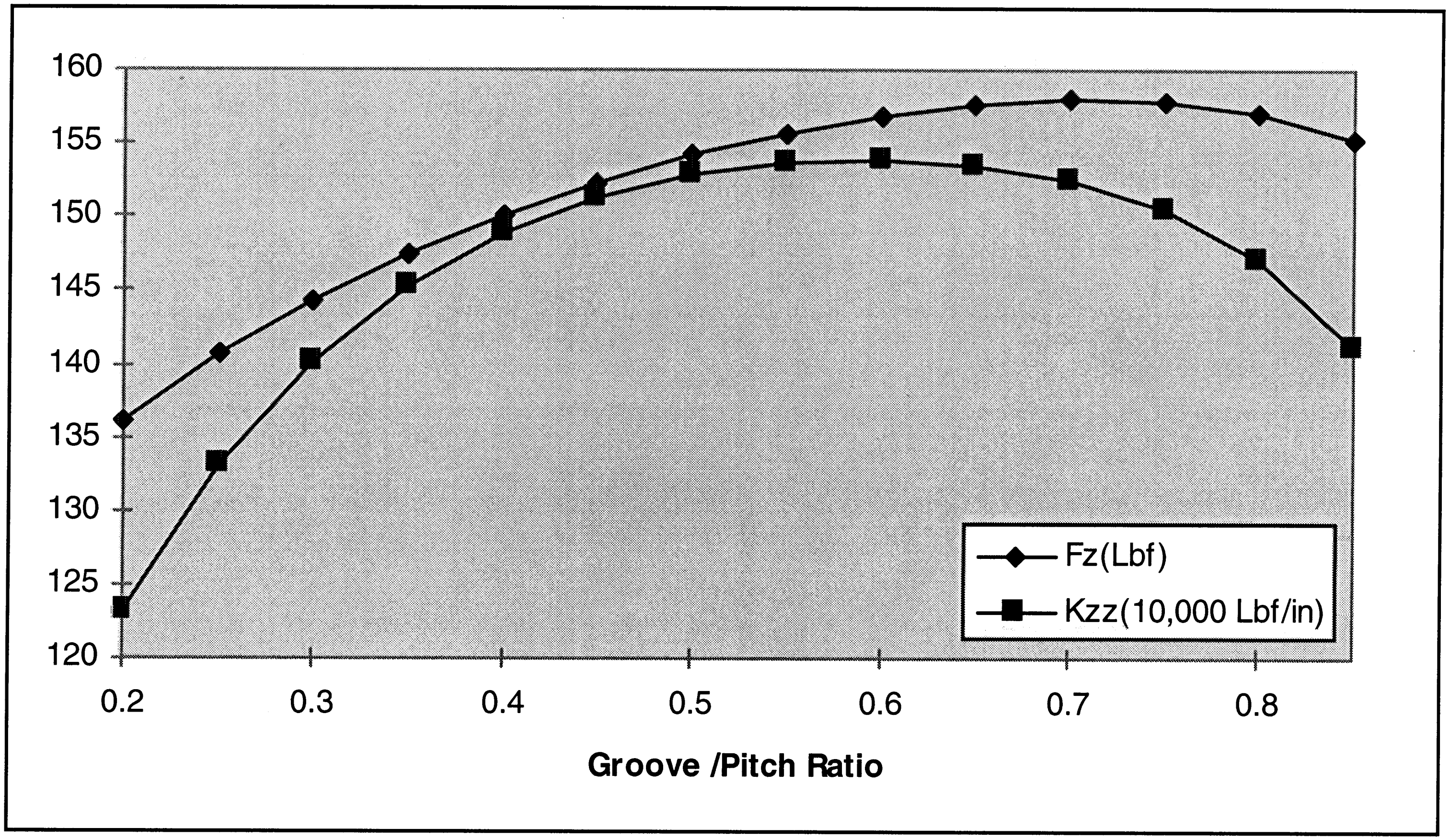
PROPOSED DUAL BRUSH SEAL





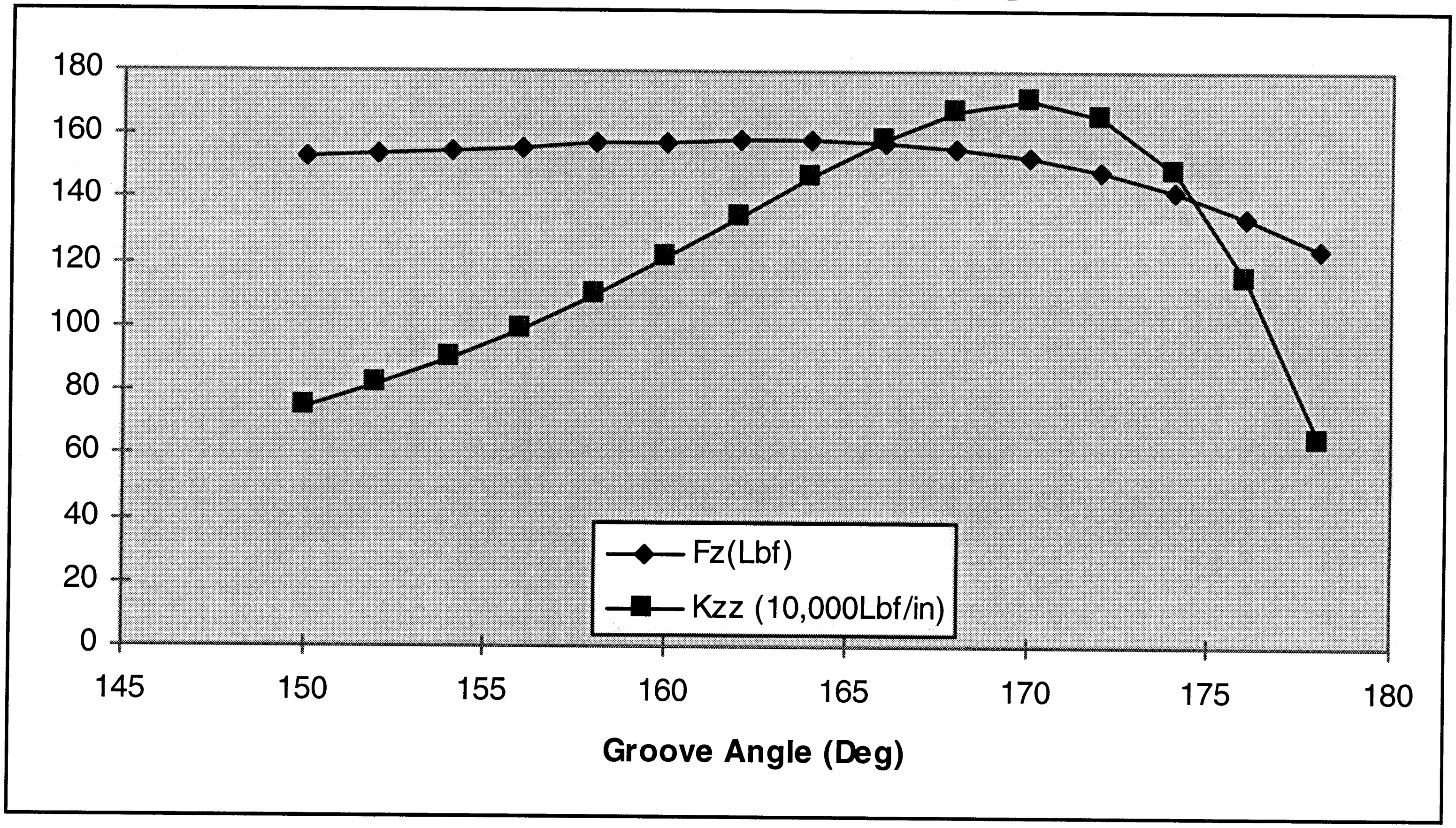


Groove width Optimization
Film load and stiffness

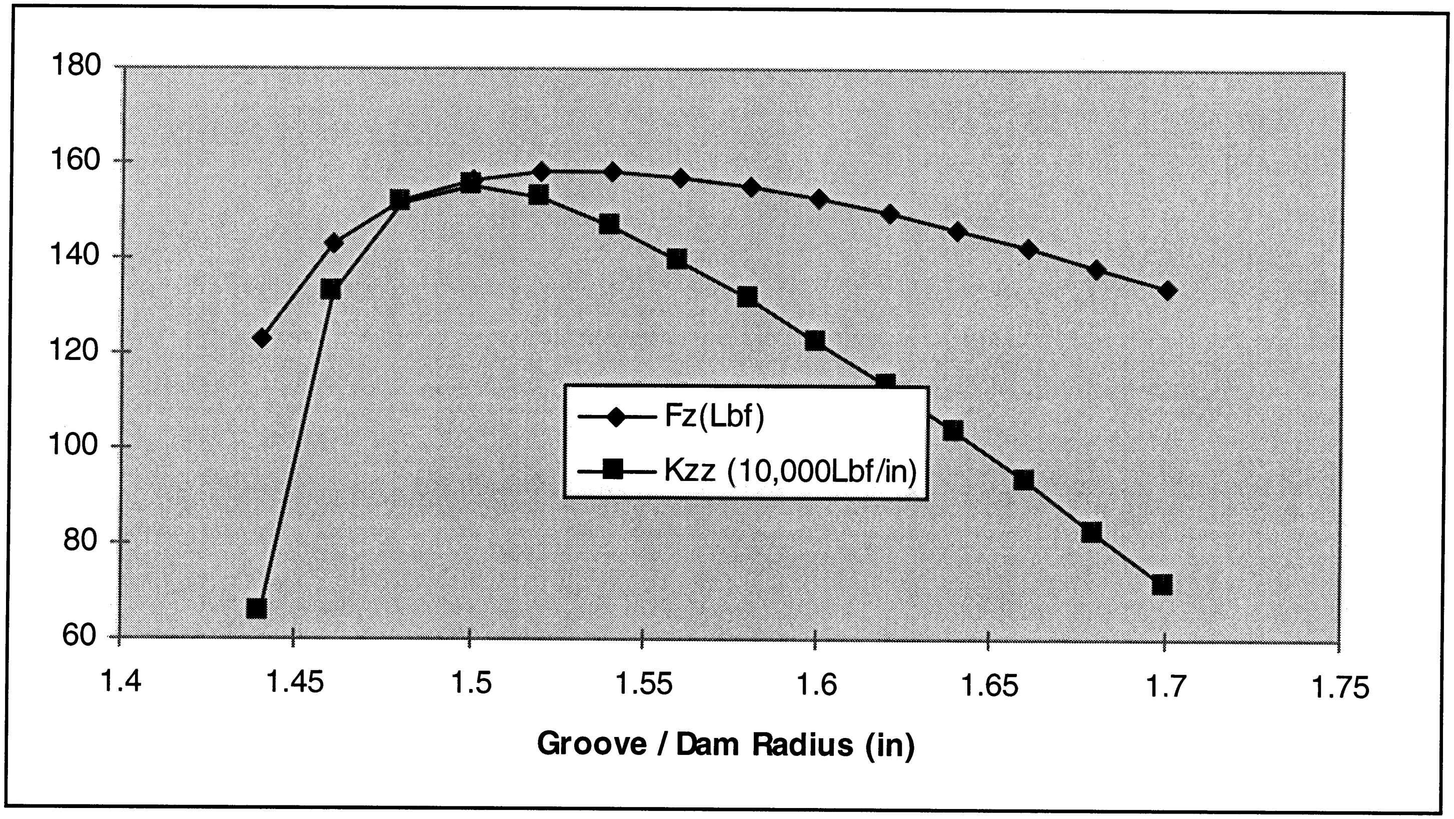


Groove angle Optimization

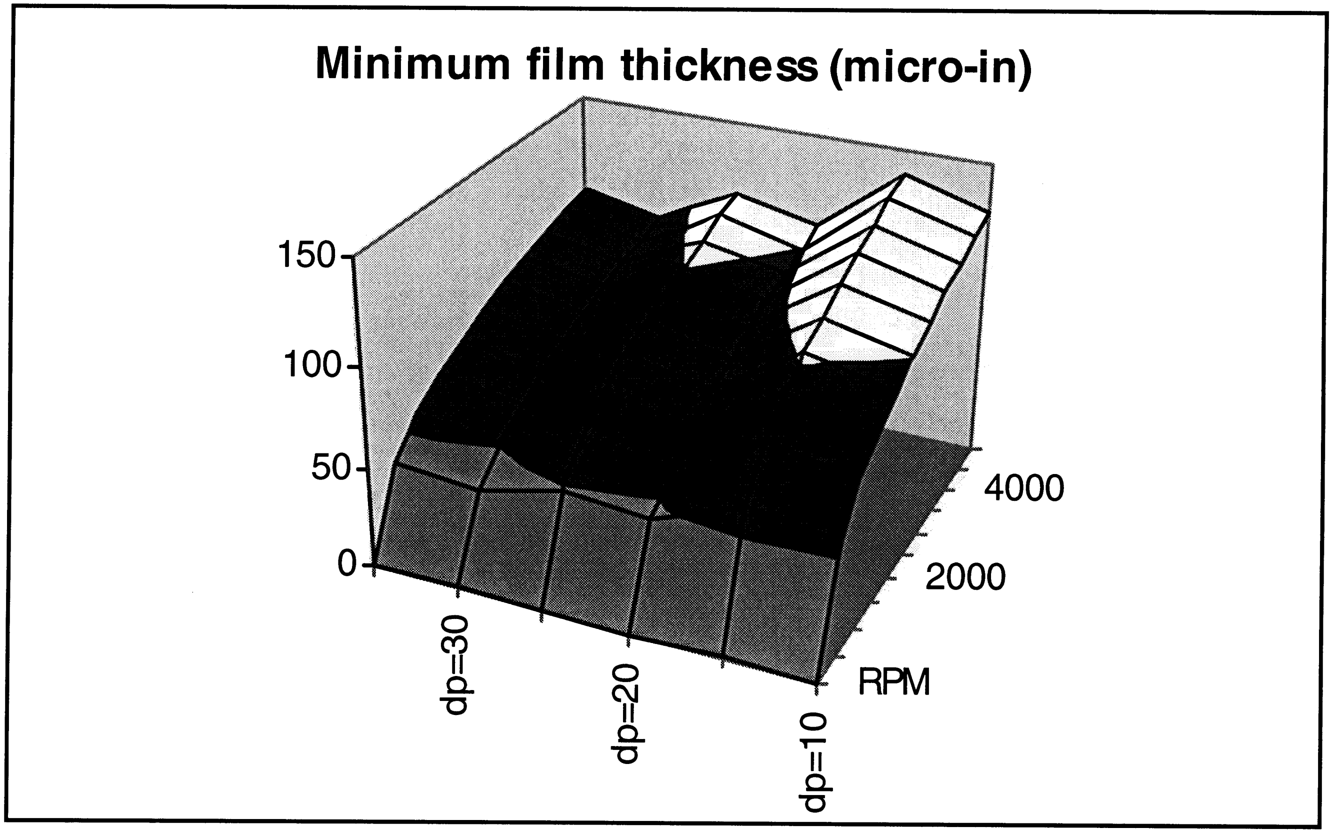
Film load and stiffness



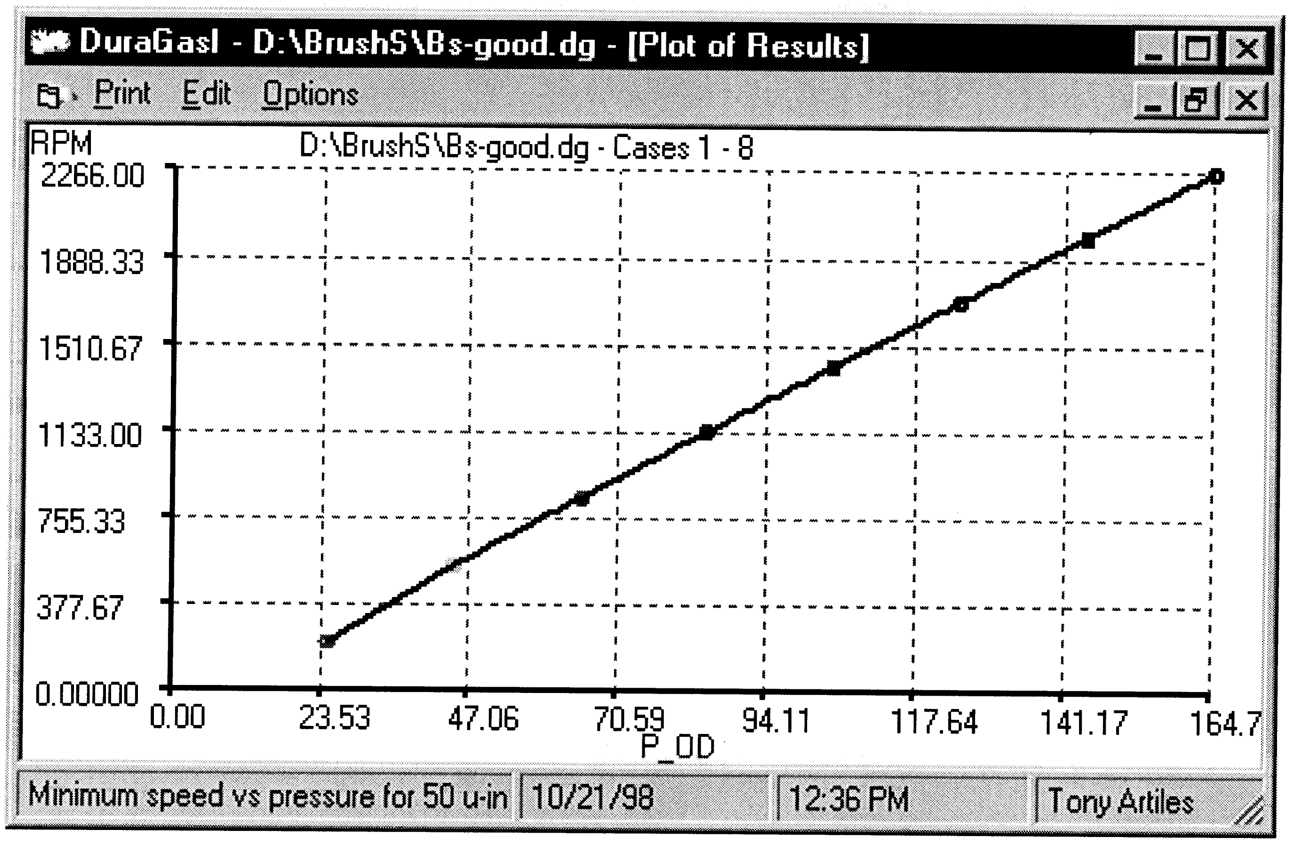
Groove radius Optimization
Film load and stiffness



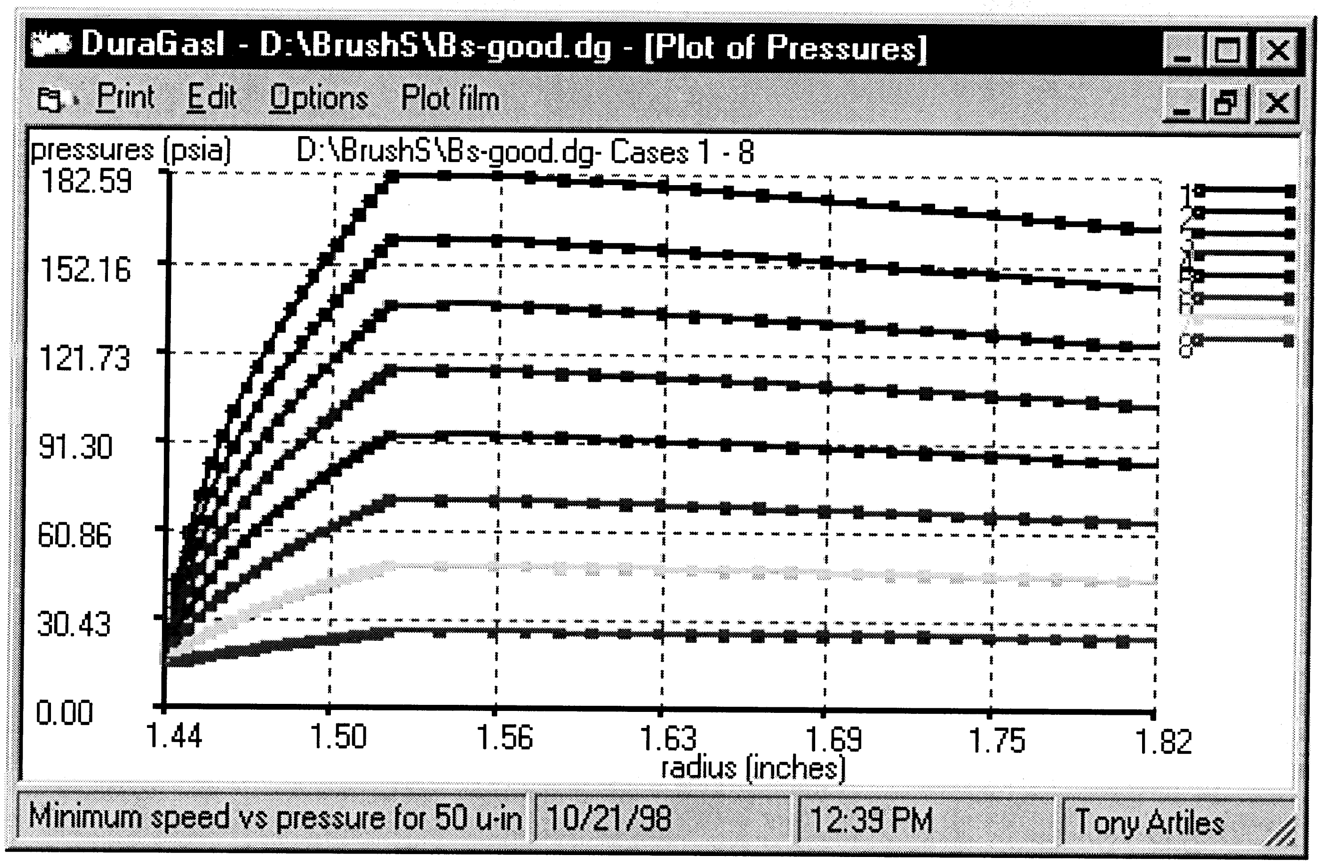
Optimized Performance
Film thickness vs. speed and pressure



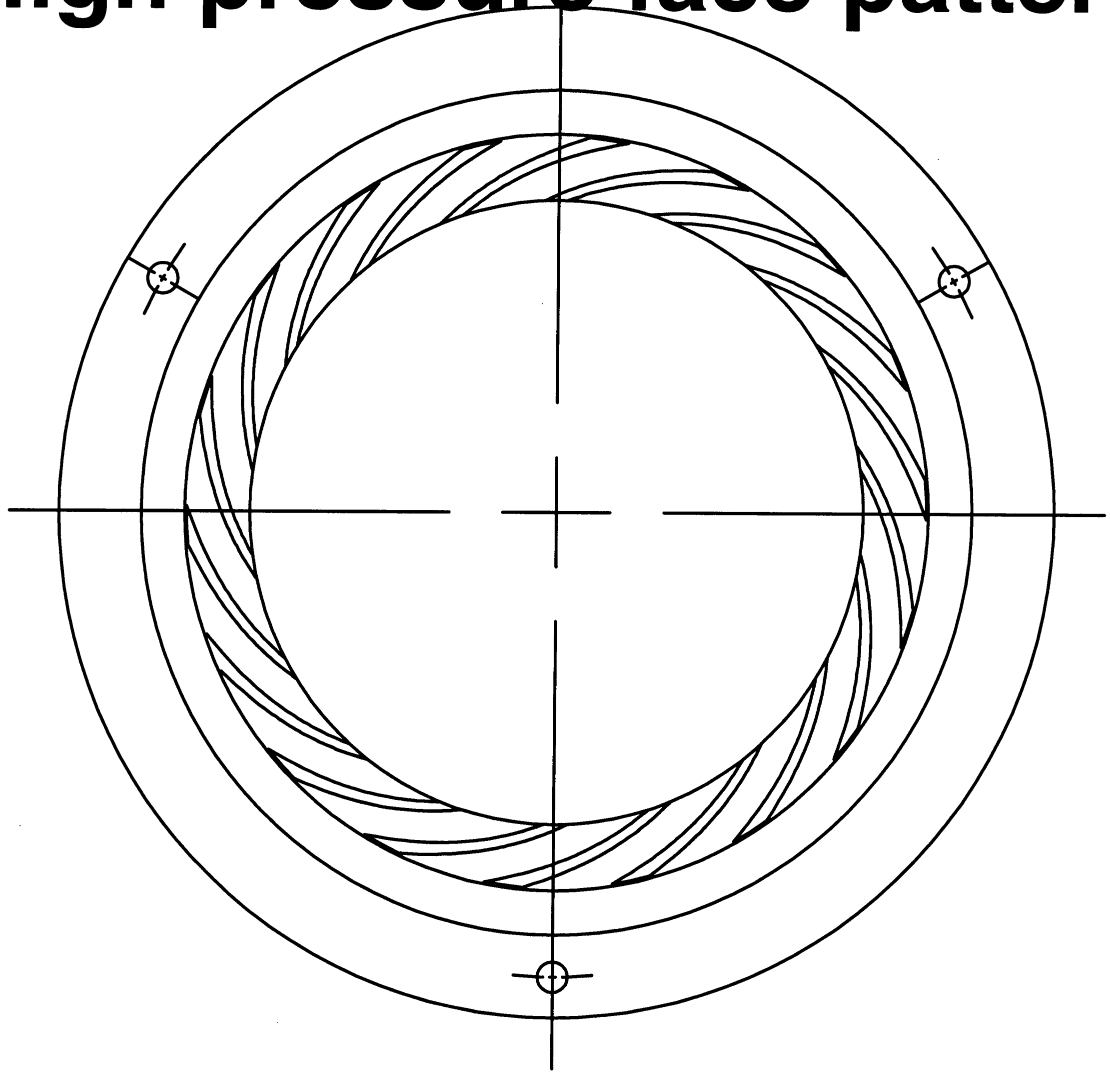
Optimized Performance
Lift-off speed vs. pressure



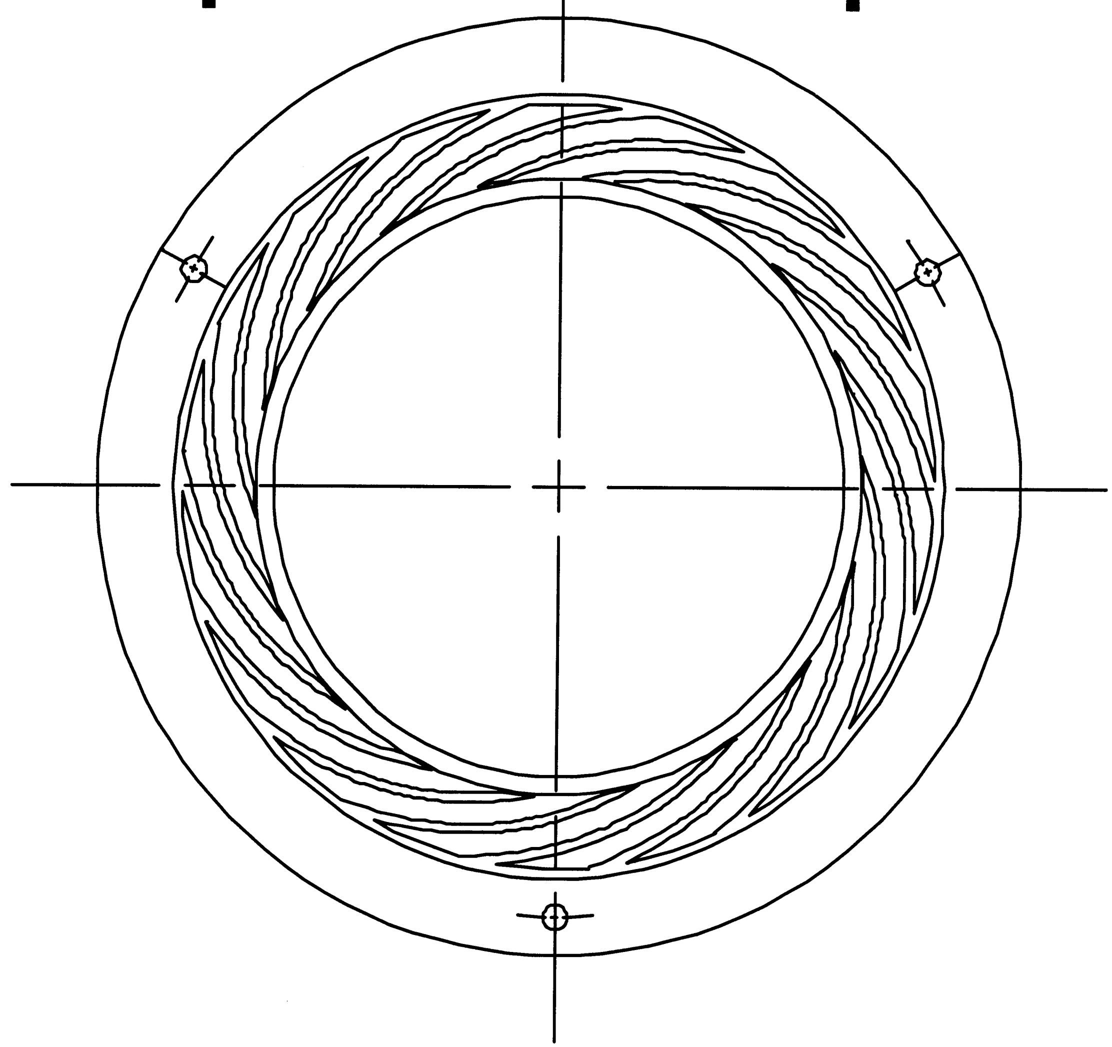
Optimized Performance
Lift-off speed vs. pressure



High pressure face pattern



Low pressure face pattern



ADVANCES IN THE HYBRID FLOATING BRUSH SEAL NOZZLE JOINT LOCATIONS

Scott Lattime and J. Braun
B&C Engineering
Akron, Ohio

HYBRID FLOATING BRUSH SEAL

- **BACKGROUND**
  - **The Hybrid Floating Brush Seal**
  - **The Room Temperature Test Rig**
  - **Brush Seal Design**

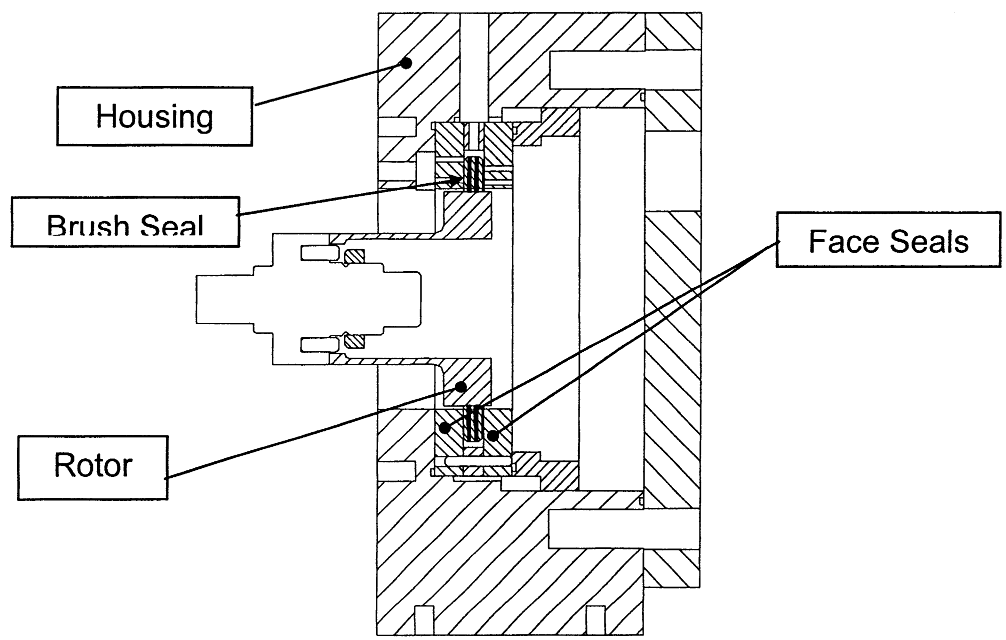
- **SUMMARY**
  - **Problems**
  - **Solutions**
  - **Achievements**

- **EXPERIMENTAL RESULTS**
  - **Leakage**
  - **Film Thickness**

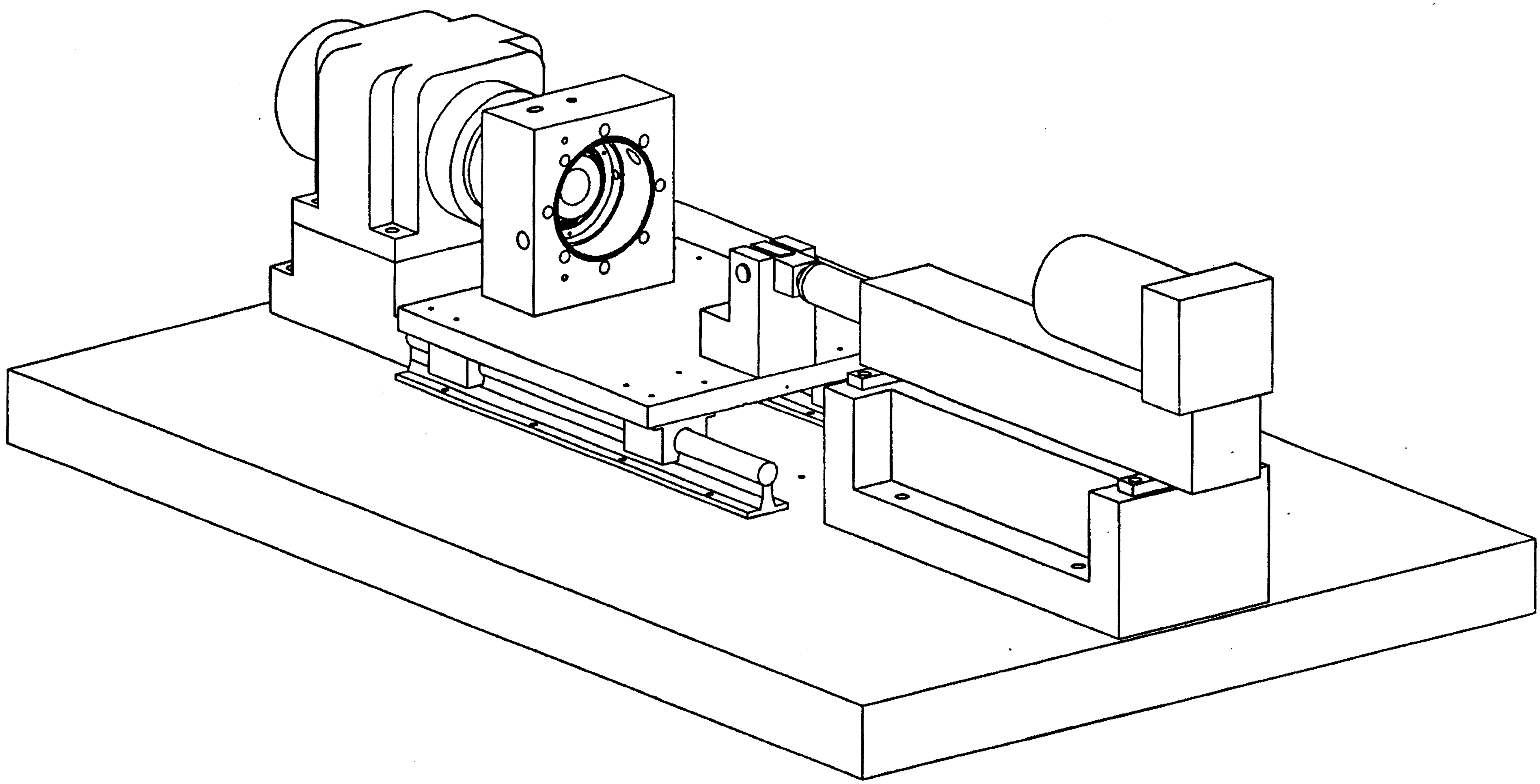
- **DIRECTION OF WORK**
  - **Goals**
  - **Tasks**

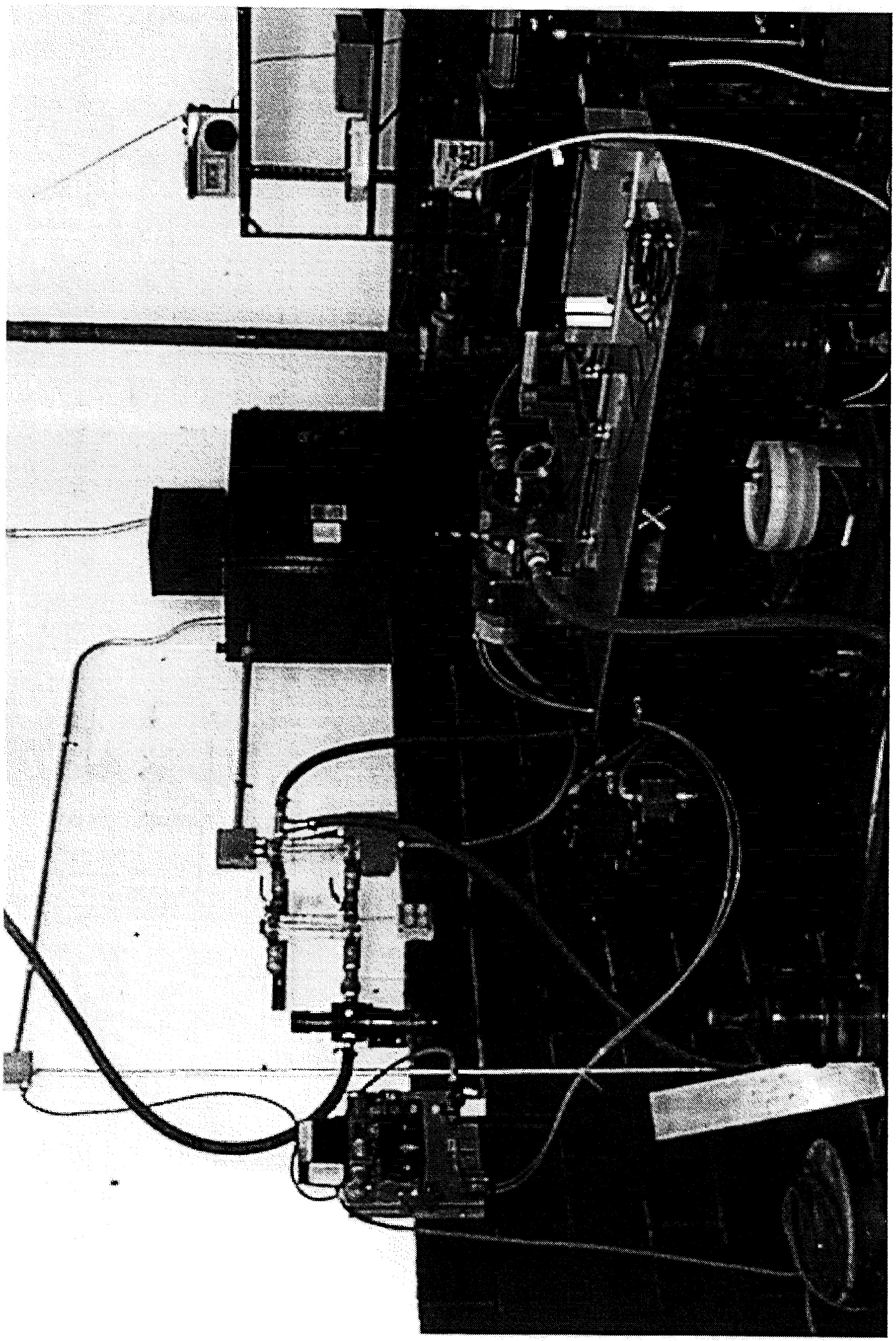
Background

The Hybrid Floating Brush Seal (HFBS)

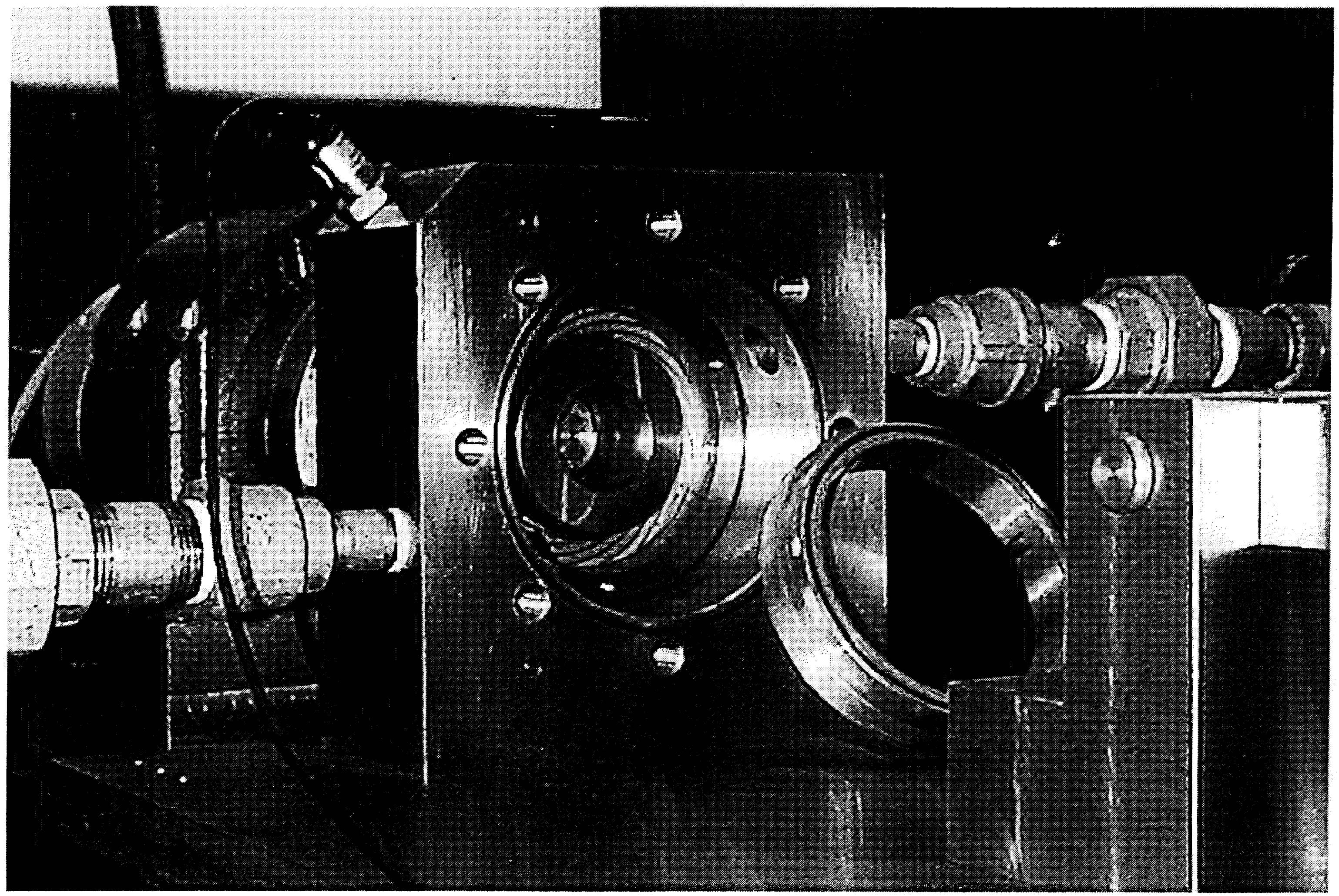


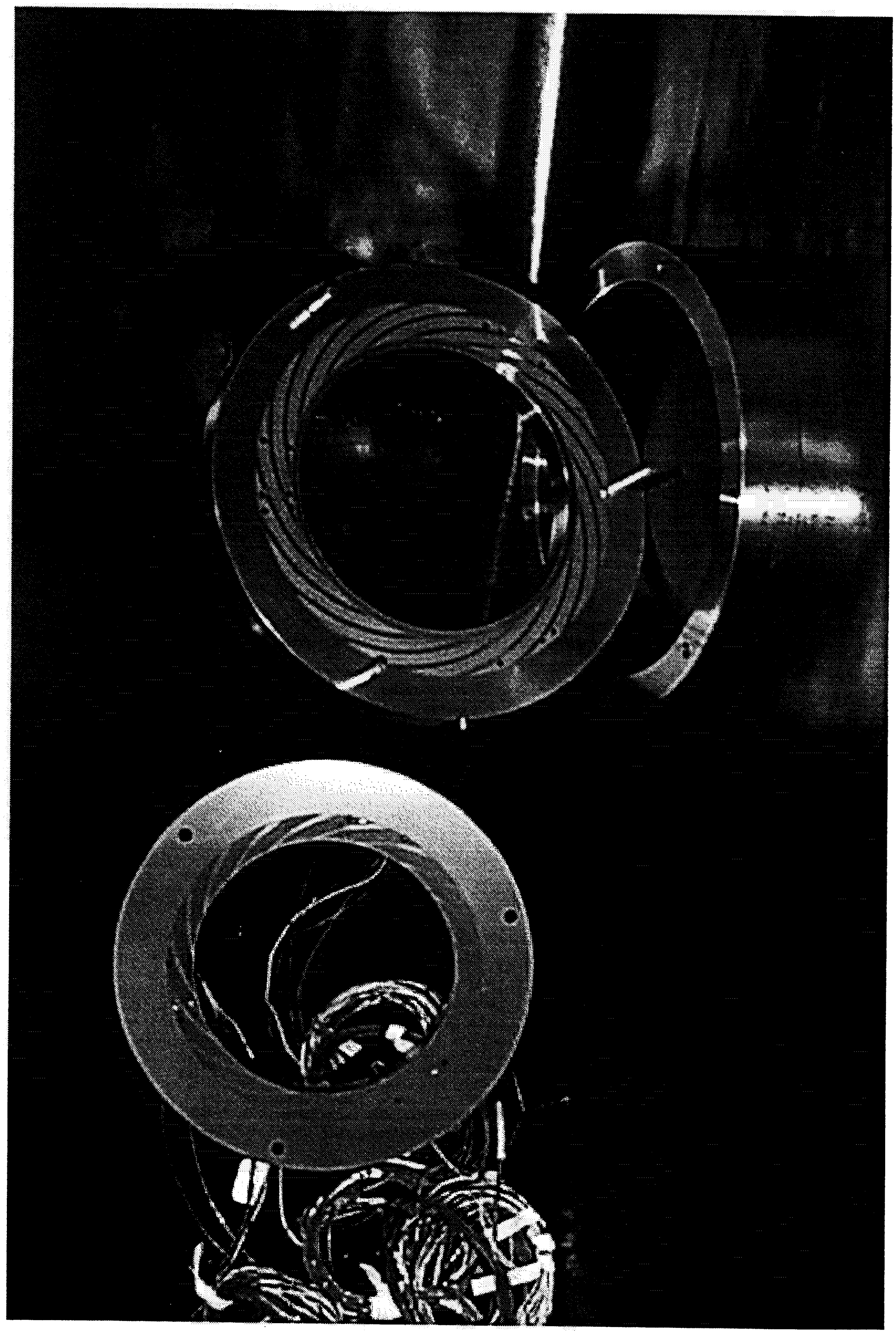
Room Temperature Test Rig (RTTR)





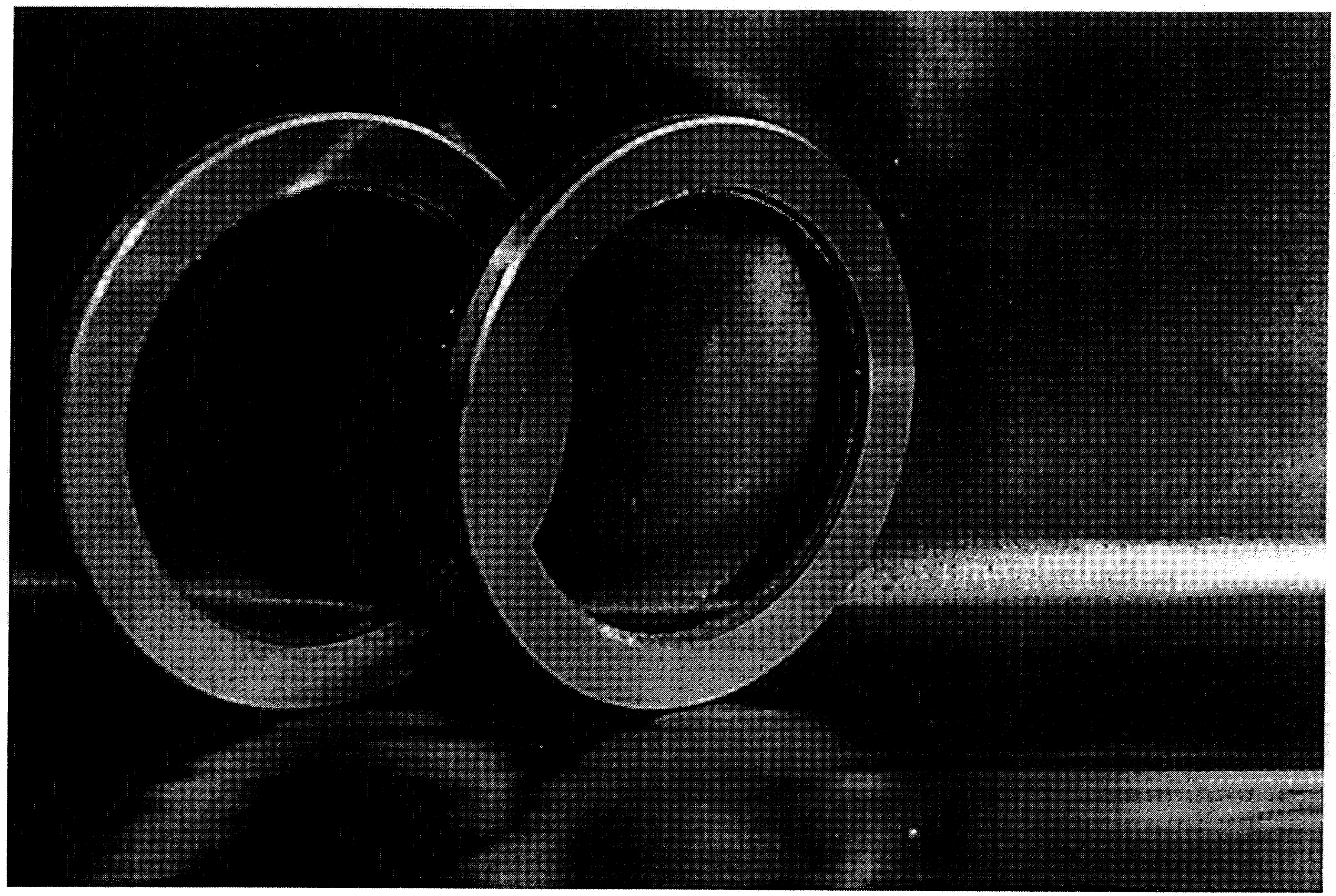
Housing





Face Seals

Brush Seals



Brush Seal Design

- The design of a brush seal for the HFBS is significantly different from that of a "standard" brush seal.

- In standard, stationary brush seals, the design focuses largely on tribo-pairing the materials of the brush and the moving rotor to reduce the wear at the interface of the two components.

- In the HFBS, the brush seal is being driven by the rotor. The design is therefore concerned with keeping the bristles from lifting off the shaft, due to centrifugal forces, to eliminate relative velocities between the two components.

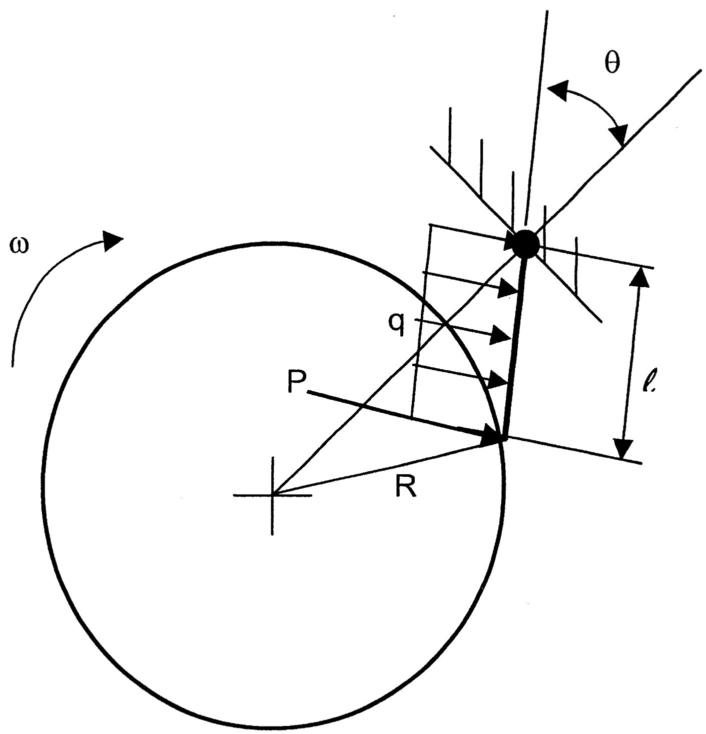
- This centripetal phenomenon was studied both analytically and experimentally.

BRISTLE DEFLECTION DUE TO CENTRIFUGAL LOAD

Consider the forces acting on a single bristle of length ℓ, diameter d, under a pre-load P, lay angle θ, and a rotational speed ω.

The pre-load is the force applied by the rotor onto the bristle, as the O.D. of the rotor pushes the end of the bristle outward radially from its center.

The deflection, δ_p, due to pre-load, P, is given by:



$$\delta_P = \frac{Pl^3}{3EI} \quad \text{where} \quad I = \frac{\pi d^4}{64}$$

$$\delta_w = \frac{ql^4}{8EI} \quad \text{where} \quad q = \frac{w \sin\theta}{l}$$

$$= \frac{wl^3 \sin\theta}{8EI} \quad \text{where} \quad w = mr\omega^2,$$

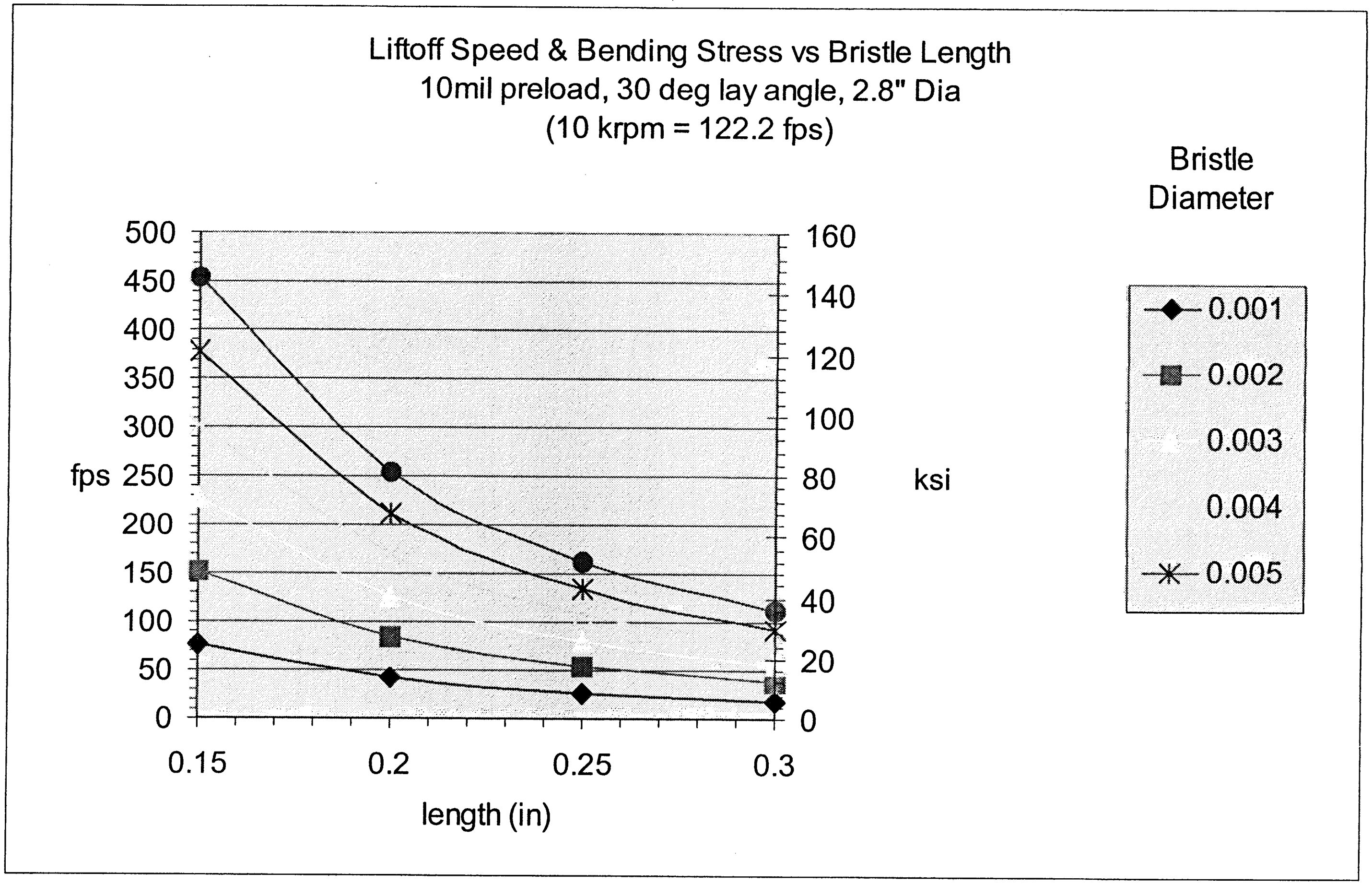
and m is the mass of the bristle

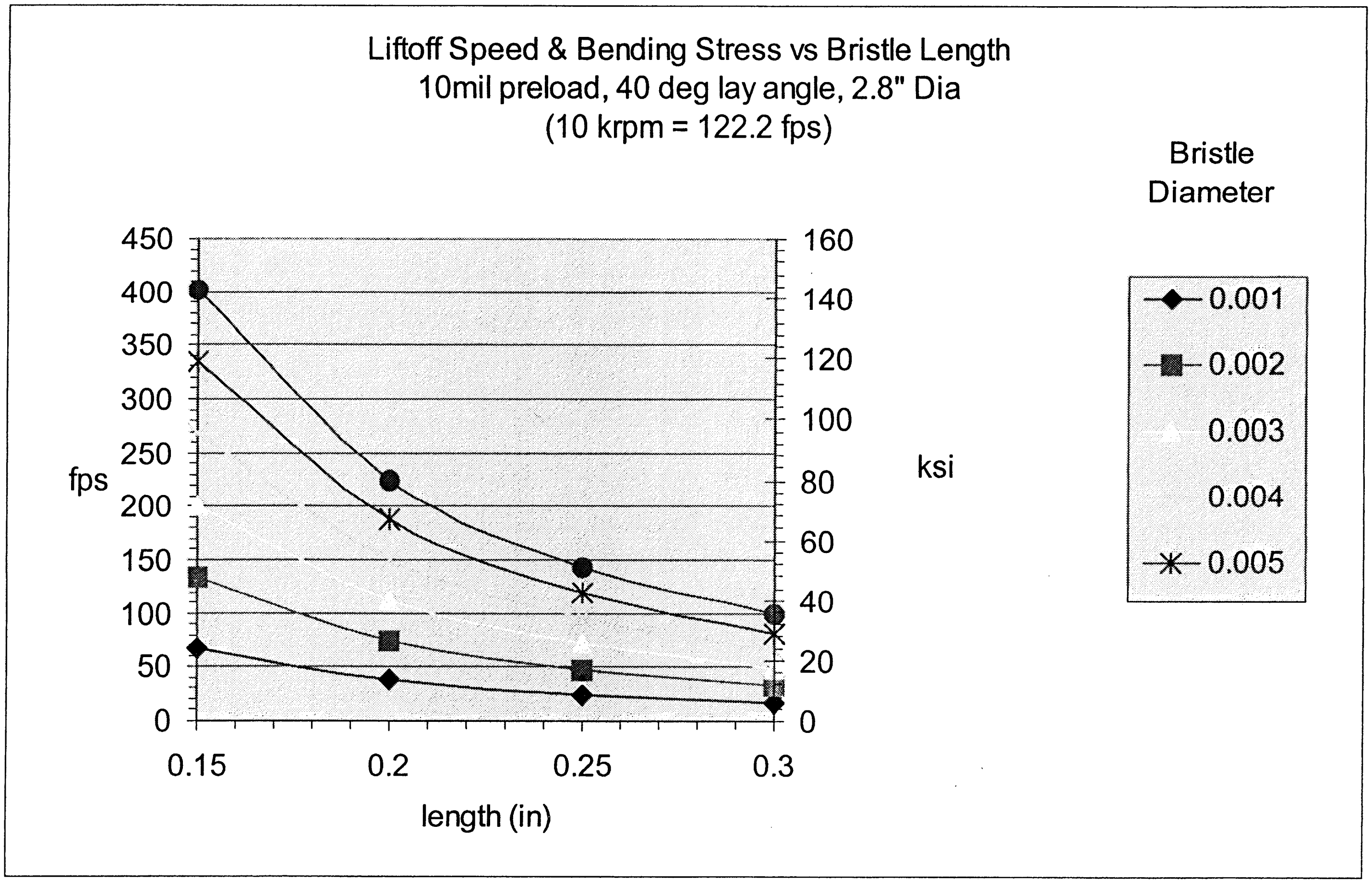
ANALYTICAL MODEL

The design process of the brush seal involved parametric calculations using the geometric characteristics and material properties of the bristles. The calculations allowed the determination of the highest rotational speed at which the bristles would begin to lift off the rotor for a given bristle geometry.

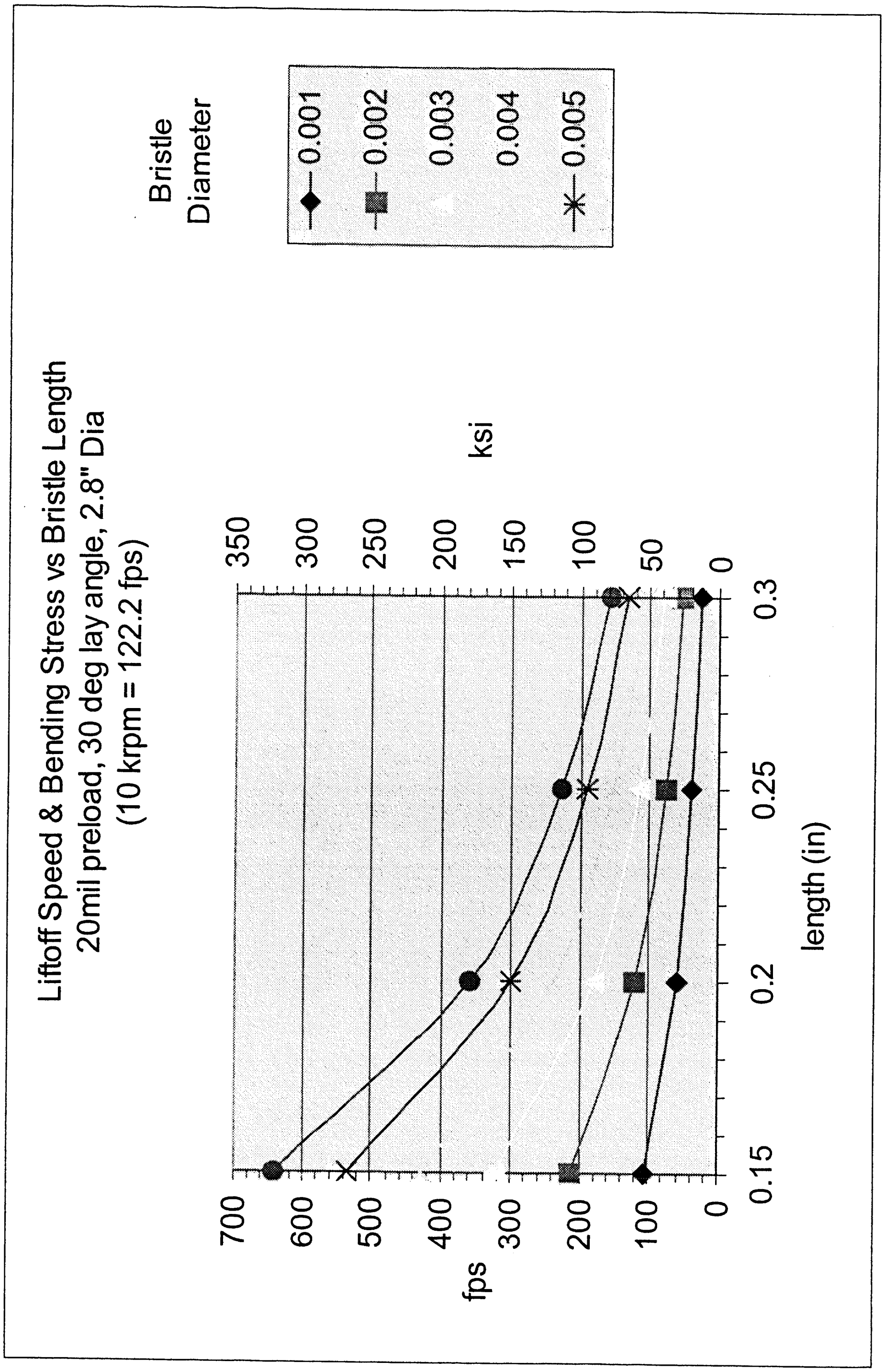
These properties included:

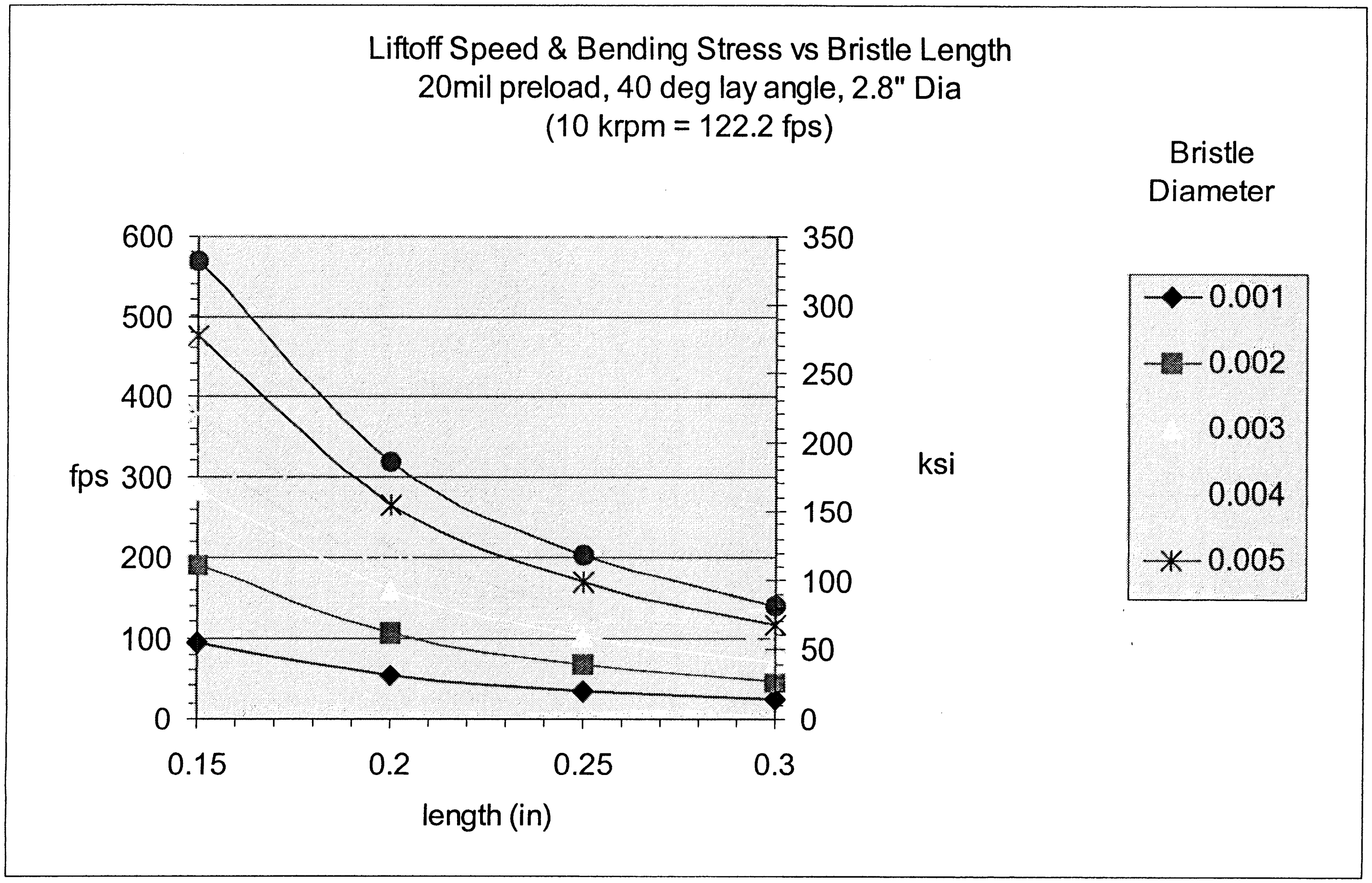
a) Free length of the bristles
b) Density and Elastic Modulus of the bristles
c) Diameter of the bristles
d) Lay angle of the bristles
e) Bristle pre-load
f) Bending stress of the bristles


Liftoff Speed & Bending Stress vs Bristle Length
10mil preload, 30 deg lay angle, 2.8" Dia
(10 krpm = 122.2 fps)
Bristle
Diameter
0.001
0.002
0.003
0.004
0.005
fps
500
450
400
350
300
250
200
150
100
50
0
ksi
160
140
120
100
80
60
40
20
0
0.15
0.2
0.25
0.3
length (in)



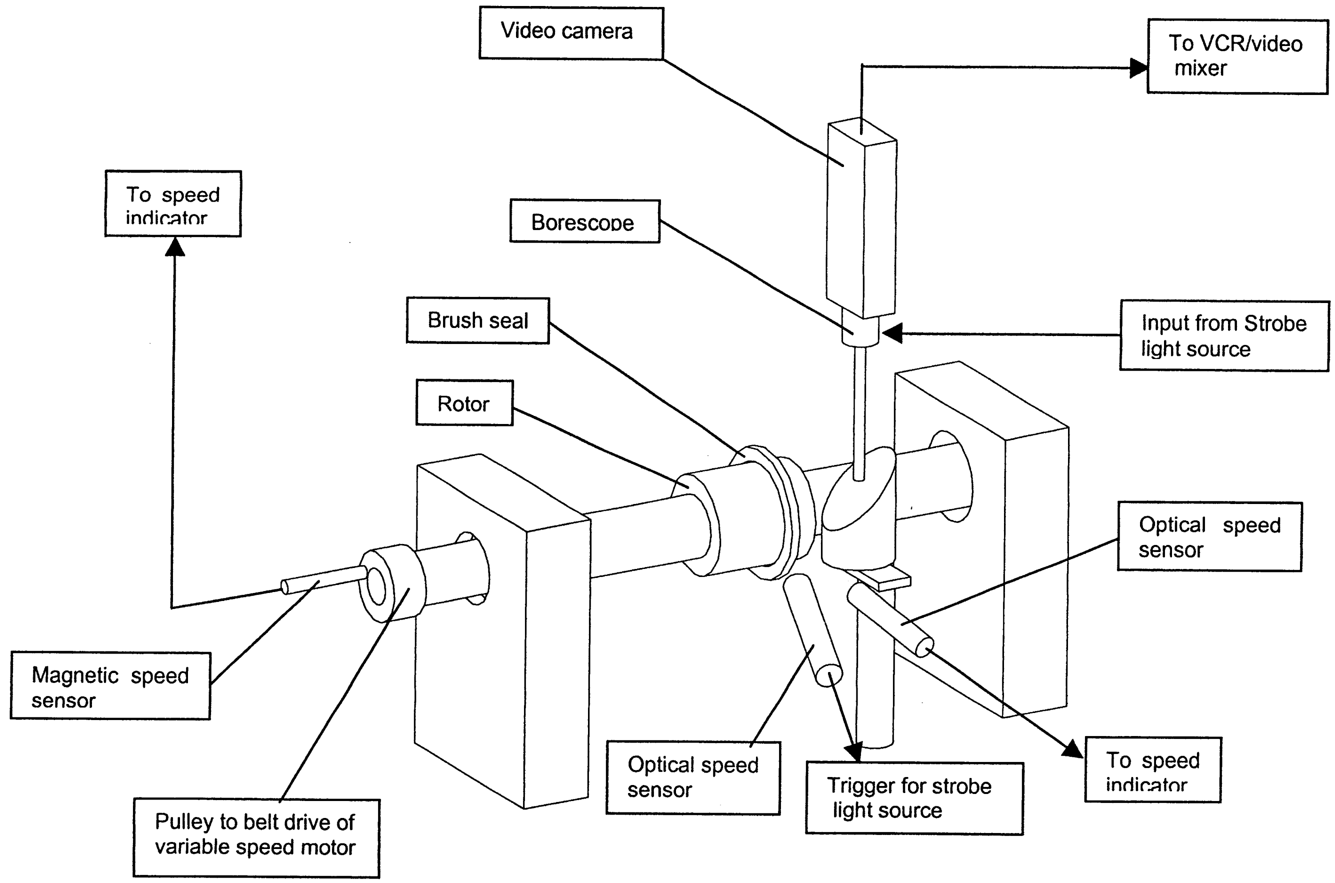
Liftoff Speed & Bending Stress vs Bristle Length
10mil preload, 40 deg lay angle, 2.8" Dia
(10 krpm = 122.2 fps)
fps
450
400
350
300
250
200
150
100
50
0
0.15
0.2
0.25
0.3
length (in)
160
140
120
100
80
60
40
20
0
ksi
Bristle Diameter
0.001
0.002
0.003
0.004
0.005


Liftoff Speed & Bending Stress vs Bristle Length
20mil preload, 30 deg lay angle, 2.8" Dia
(10 krpm = 122.2 fps)
fps
ksi
length (in)
Bristle
Diameter
0.001
0.002
0.003
0.004
0.005
0
100
200
300
400
500
600
700
0
50
100
150
200
250
300
350
0.15
0.2
0.25
0.3



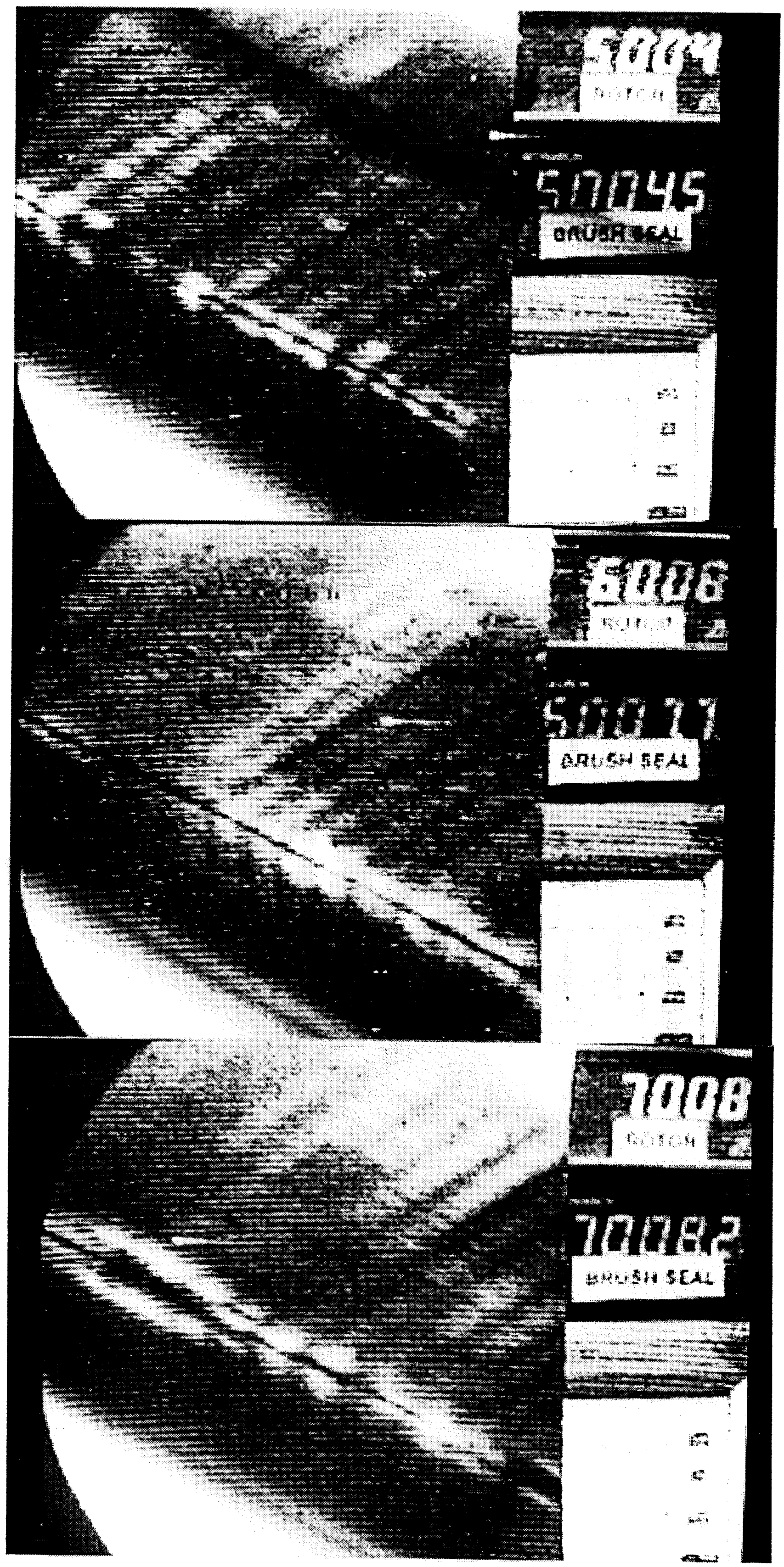
Liftoff Speed & Bending Stress vs Bristle Length
20mil preload, 40 deg lay angle, 2.8" Dia
(10 krpm = 122.2 fps)
fps
ksi
length (in)
Bristle
Diameter
0.001
0.002
0.003
0.004
0.005

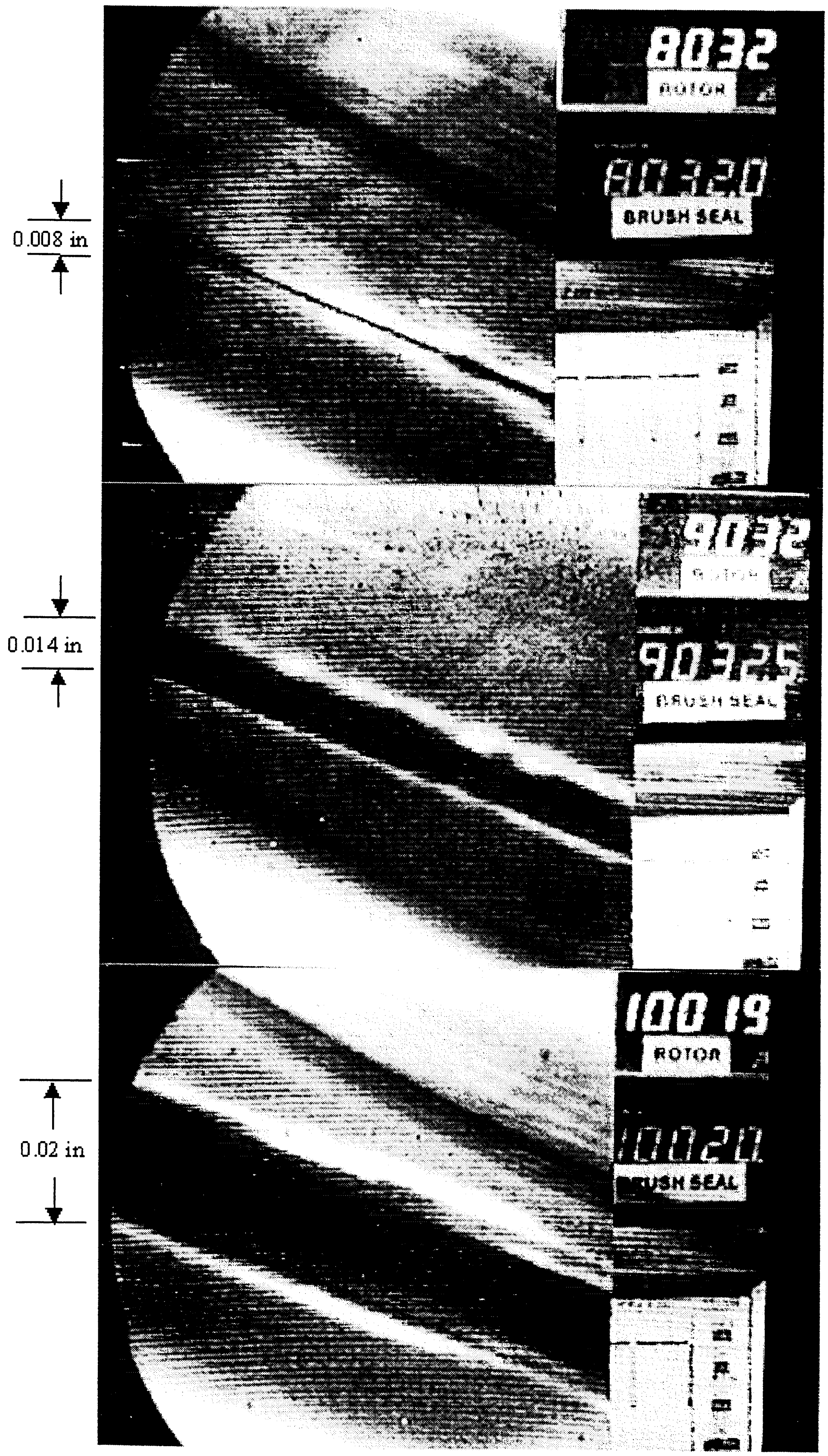
EXPERIMENTAL ANALYSIS



0.002 in

0.006 in





0.008 in
0.014 in
0.02 in
8032
ROTOR
BRUSH SEAL
ROTOR
BRUSH SEAL
100 19
ROTOR
BRUSH SEAL


9516
ROTOR
BRUSH SEAL
10024
BRUSH SEAL
11038
ROTOR
BRUSH SEAL

SUMMARY

Problems

1. Face seal material. Due to thermal expansion considerations, the material chosen for the face seals (Inconel 909) was similar to the material used for the side plates of the brush seal (Hastelloy X). This material matching proved to be a detrimental in the start-up of this hybrid seal. In addition, the face seal manufacturer had a difficult time maintaining the flatness tolerance of the stators.

2. Brush seal design. Due to the manufacturer's concerns regarding bristle bending stress, conservative brush seal designs were approached to "get the ball rolling". Premature lifting of the bristles (well below the target speed, 40krpm) occurred with these initial designs due to a lack of bristle stiffness.

Solutions

1. Face seal material. Face seals were made of a material that the manufacturer was familiar with (Silicon Carbide). This material matches very well to the brush seal side plate material at room temperature. However, another material had to be chosen to meet the target temperature (900°F), while still keeping the hardness properties of Silicon Carbide. Silicon Nitride was recommended by the face seal manufacturer. It possesses the desired properties and will be tested in the High Temperature Test Rig (HTTR).

2. Brush seal design. Using beam deflection equations, a model was developed to predict bristle lift-off, stress, and the possibility of buckling due to centrifugal forces. This model was then used to develop bristle/rotor geometries that would allow the brush seal to reach its target speed while staying within allowable bending stress ranges.

Achievements

- The face and brush seal material matching problems were solved successfully.

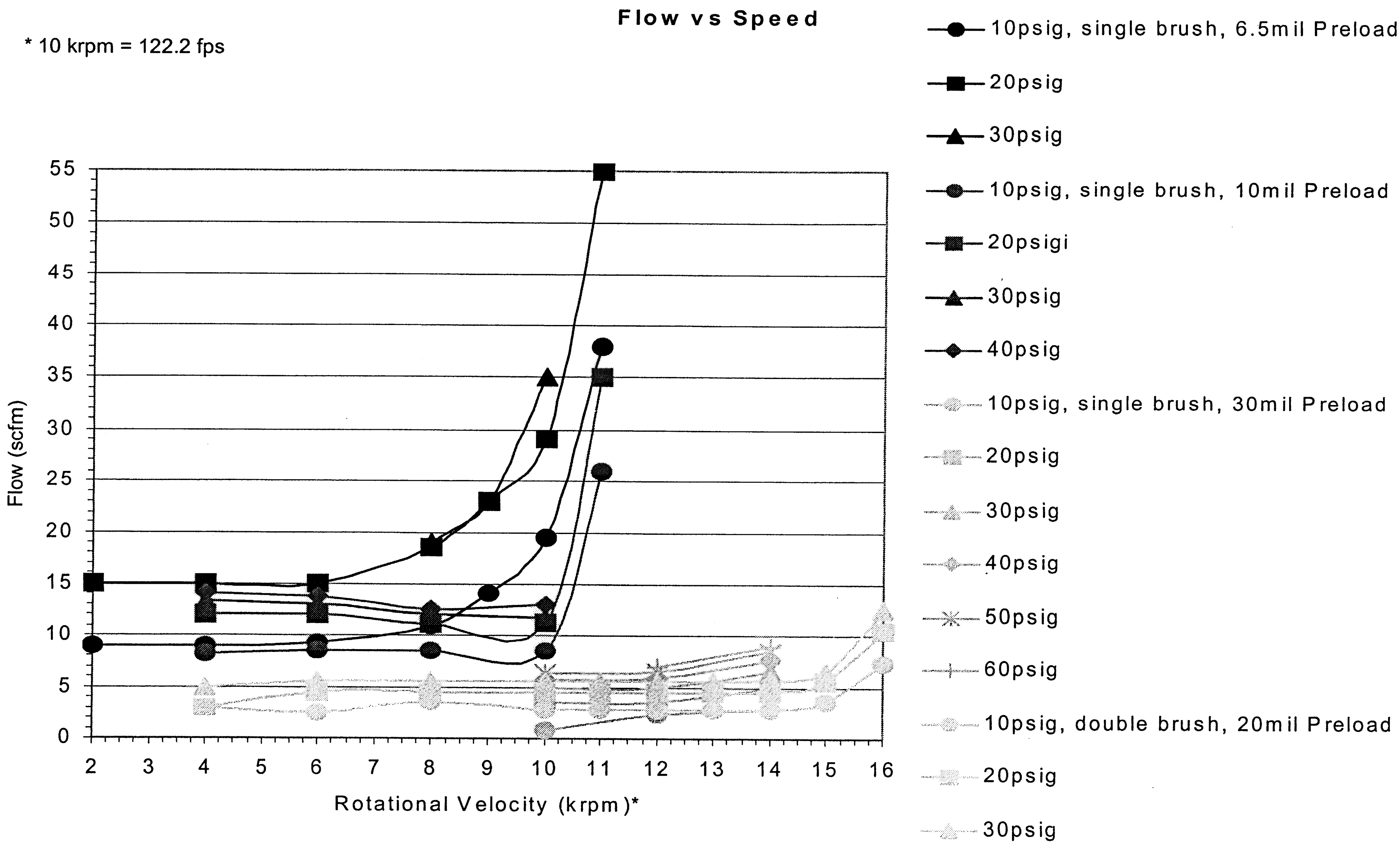
- The Hybrid Floating Brush Seal (HFBS) has proven feasibility for both low and high speed applications. Current testing of the HFBS has successfully run up to 16,000rpm at 40psi (double brush) and 1,800rpm at 100psi (single and double brush).

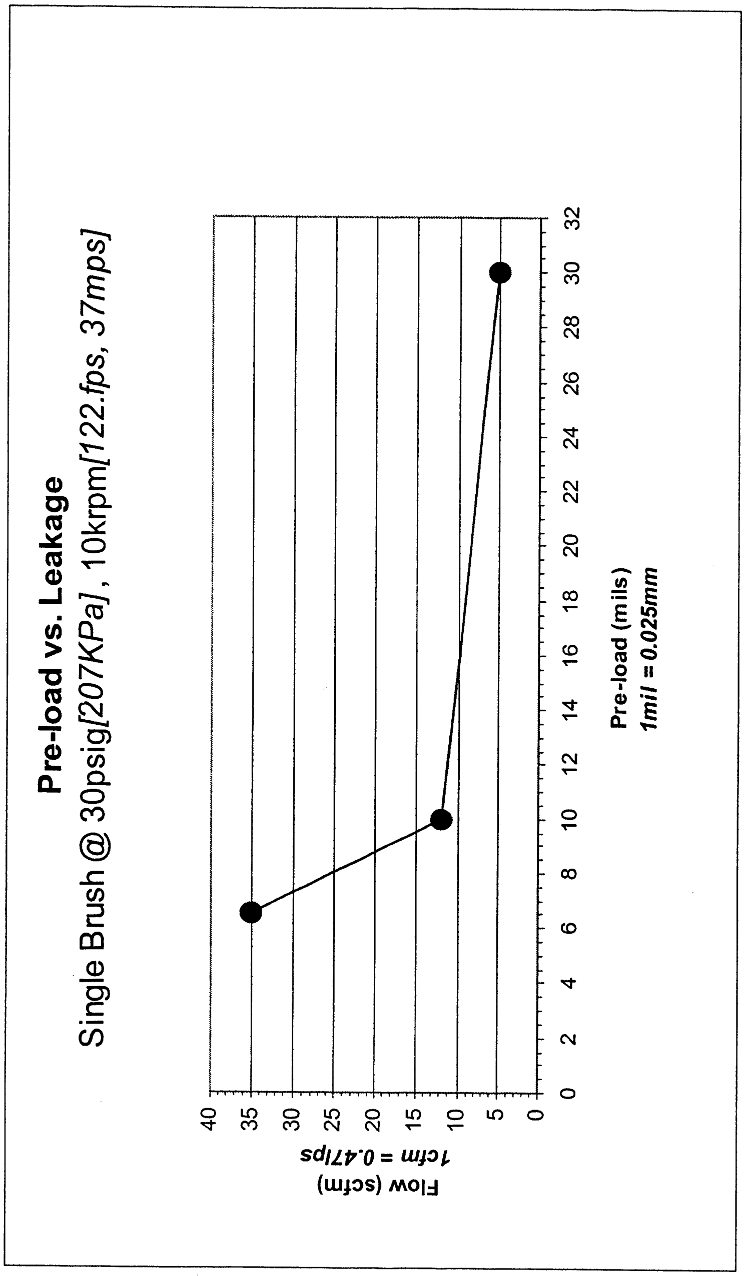
- New brush seal suppliers have been approached to fabricate the brush seals at a much lower cost than the current supplier. Companies show great interest in the HFBS concept and the chance for designing and testing new types of brushes for both high and low speed applications. A brush seal manufacturer will be a prominent component for success in phase III (commercialization).

- BCEA has developed an analytical model that has been used for the new brush seal designs. The experiments planned for the near future are intended to validate the model and provide the desired types of brushes for the successful conclusion of the project.

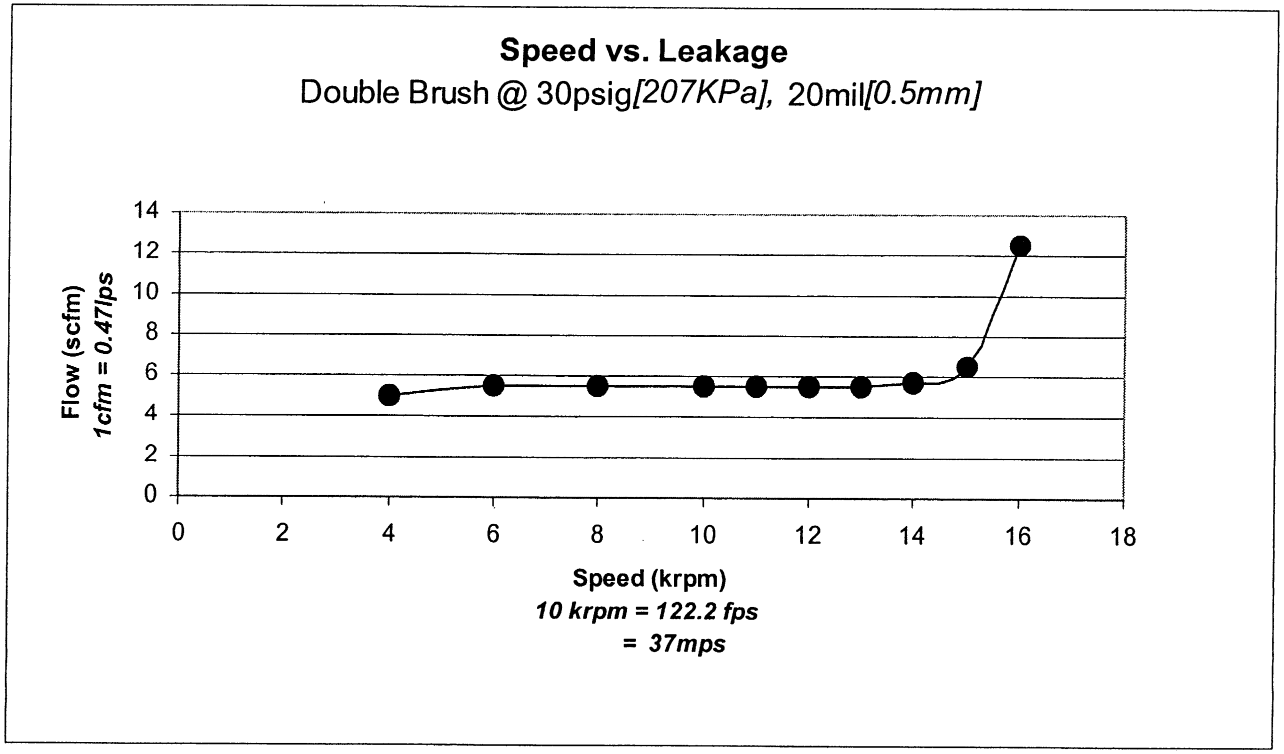
Experimental Results

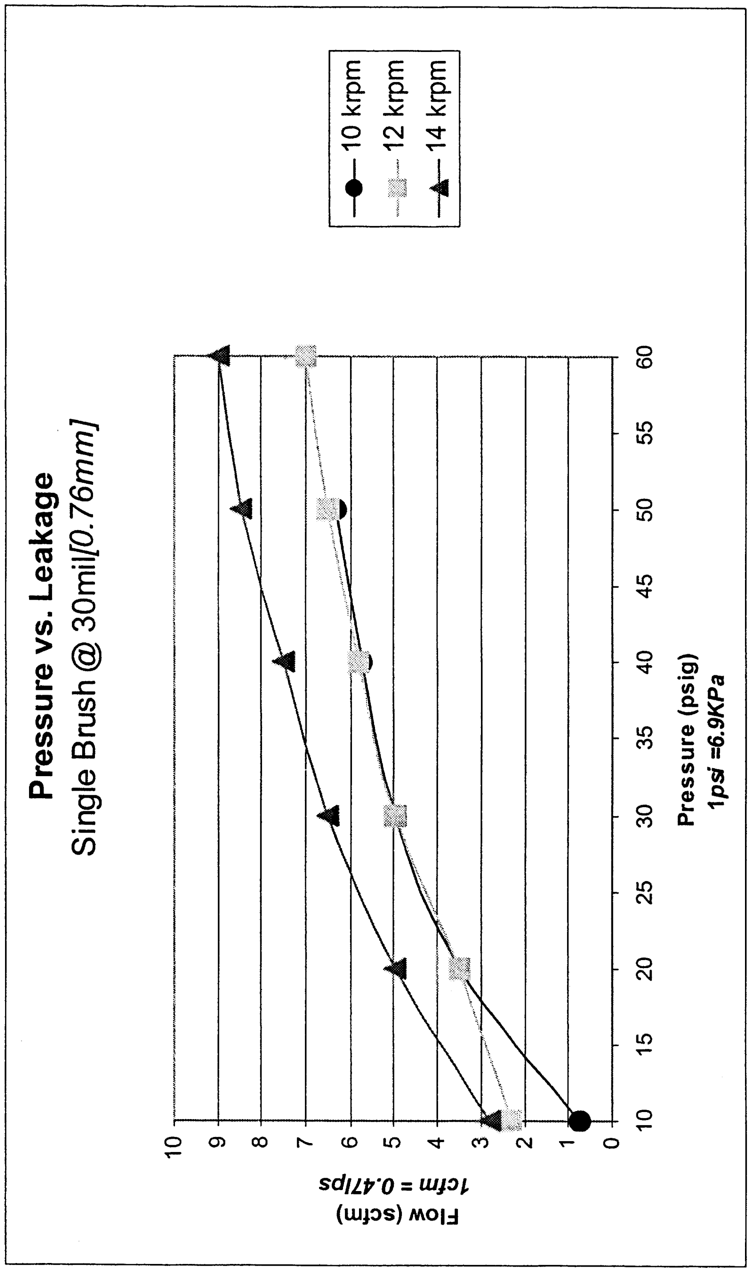
* 10 krpm = 122.2 fps



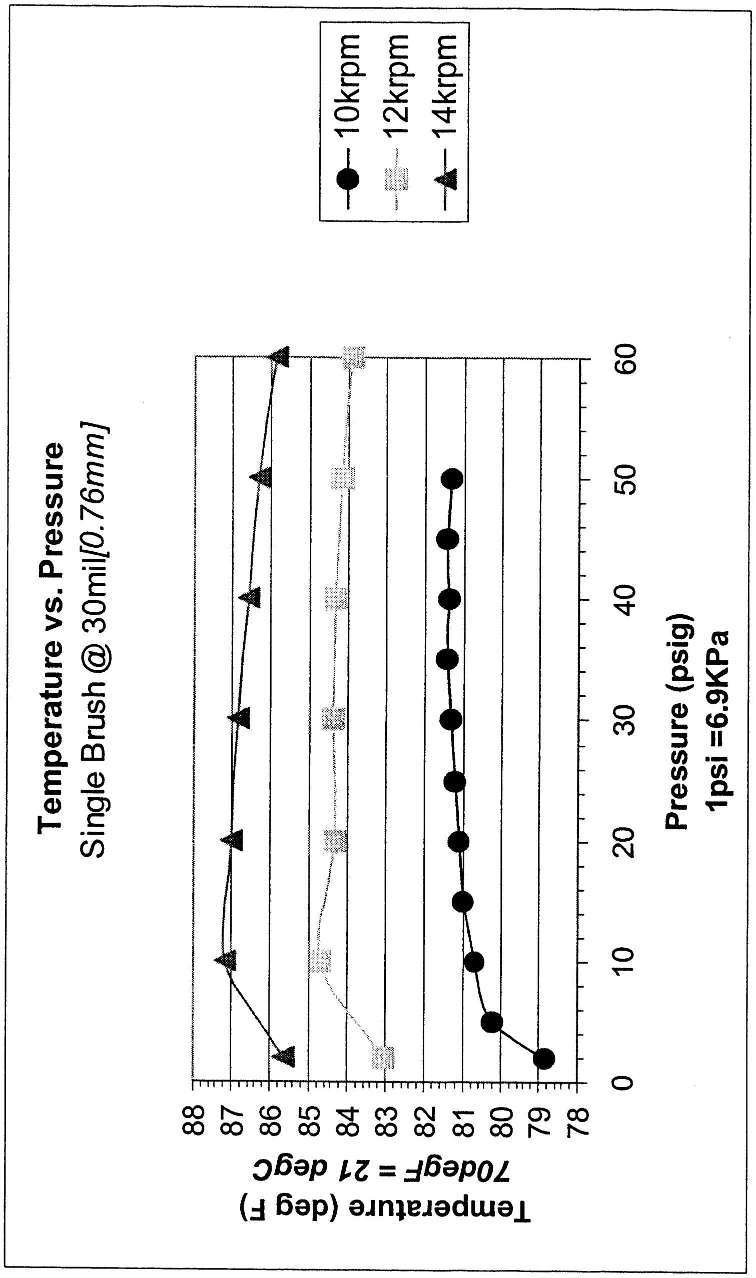


Pre-load vs. Leakage
Single Brush @ 30psig[207KPa], 10krpm[122.fps, 37mps]
Flow (scfm)
1cfm = 0.47lps
0
5
10
15
20
25
30
35
40
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
Pre-load (mils)
1mil = 0.025mm

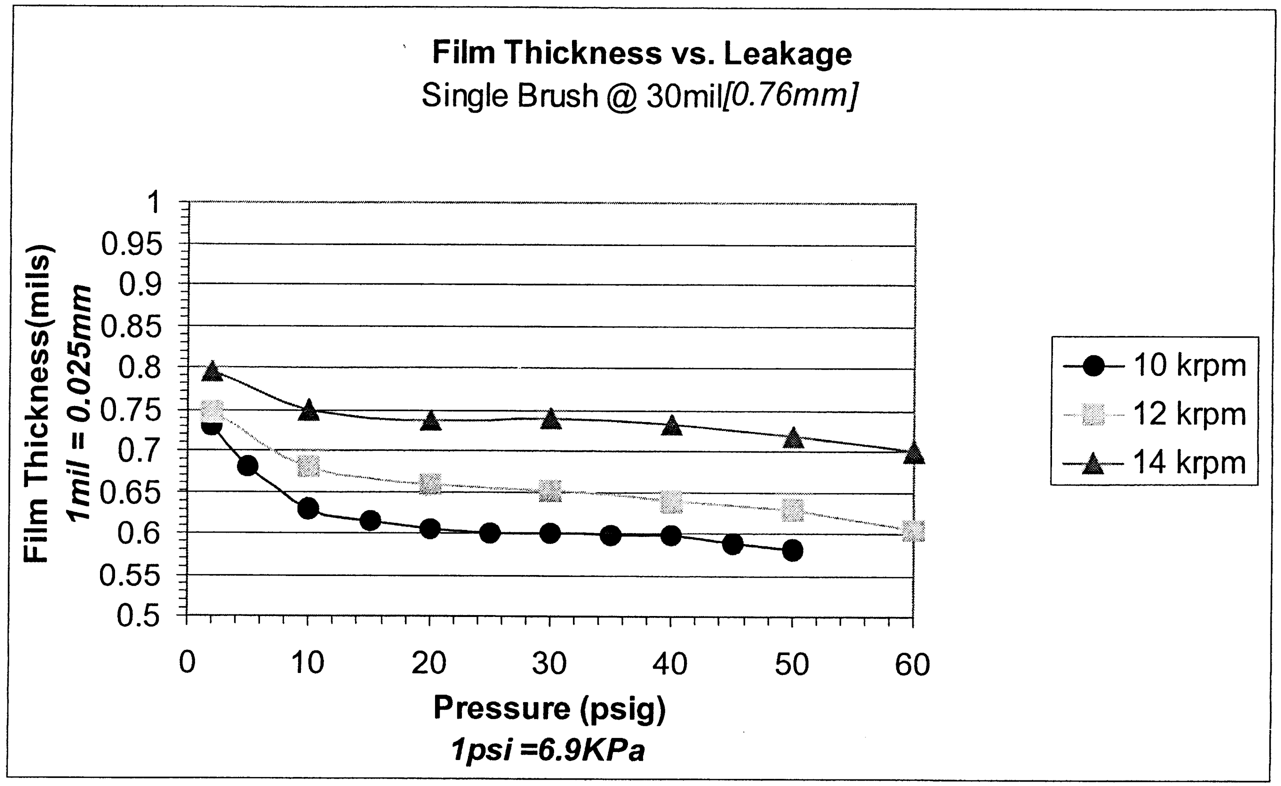

Speed vs. Leakage
Double Brush @ 30psig[207KPa], 20mil[0.5mm]
Flow (scfm)
1cfm = 0.47lps
14
12
10
8
6
4
2
0
0
2
4
6
8
10
12
14
16
18
Speed (krpm)
10 krpm = 122.2 fps
= 37mps



Pressure vs. Leakage
Single Brush @ 30mil[0.76mm]
Flow (scfm)
1cfm = 0.47lps
Pressure (psig)
1psi =6.9KPa
10 krpm
12 krpm
14 krpm



Temperature vs. Pressure
Single Brush @ 30mil[0.76mm]
Temperature (deg F)
70degF = 21 degC
88
87
86
85
84
83
82
81
80
79
78
0
10
20
30
40
50
60
Pressure (psig)
1psi =6.9KPa
10krpm
12krpm
14krpm



Film Thickness vs. Leakage
Single Brush @ 30mil[0.76mm]
Film Thickness(mils)
1mil = 0.025mm
1
0.95
0.9
0.85
0.8
0.75
0.7
0.65
0.6
0.55
0.5
0
10
20
30
40
50
60
Pressure (psig)
1psi =6.9KPa
10 krpm
12 krpm
14 krpm

Direction of Work

Goals

- Design brush seal to run at speeds of 40krpm and beyond.
- Optimize seal performance for both high (turbine, jet engines) and low (compressors, pumps) speed applications.
- Obtain partners and support for commercialization of the HFBS in both high and low speed rotating machinery markets.

Tasks

- Study bristle lifting and leakage characteristics at speeds up to 40krpm and pressures up to 120psi.
- Examine the effects of bristle geometry: diameter, length, lay angle, and density.
- Comparison/ validation of bristle lift model to experimental results.
- Test effects of radial runout and rotor axial motion on seal performance.
- Evaluate start up conditions under pressure load and ramping up pressure and speed.
- Examine bristle hysteresis and possible permanent deformation
- After confidence is reached at room temperature, test seal performance up to 900°F.

FEASIBILITY ASSESSMENT OF THERMAL BARRIERS
FOR RSRM NOZZLE JOINT LOCATIONS

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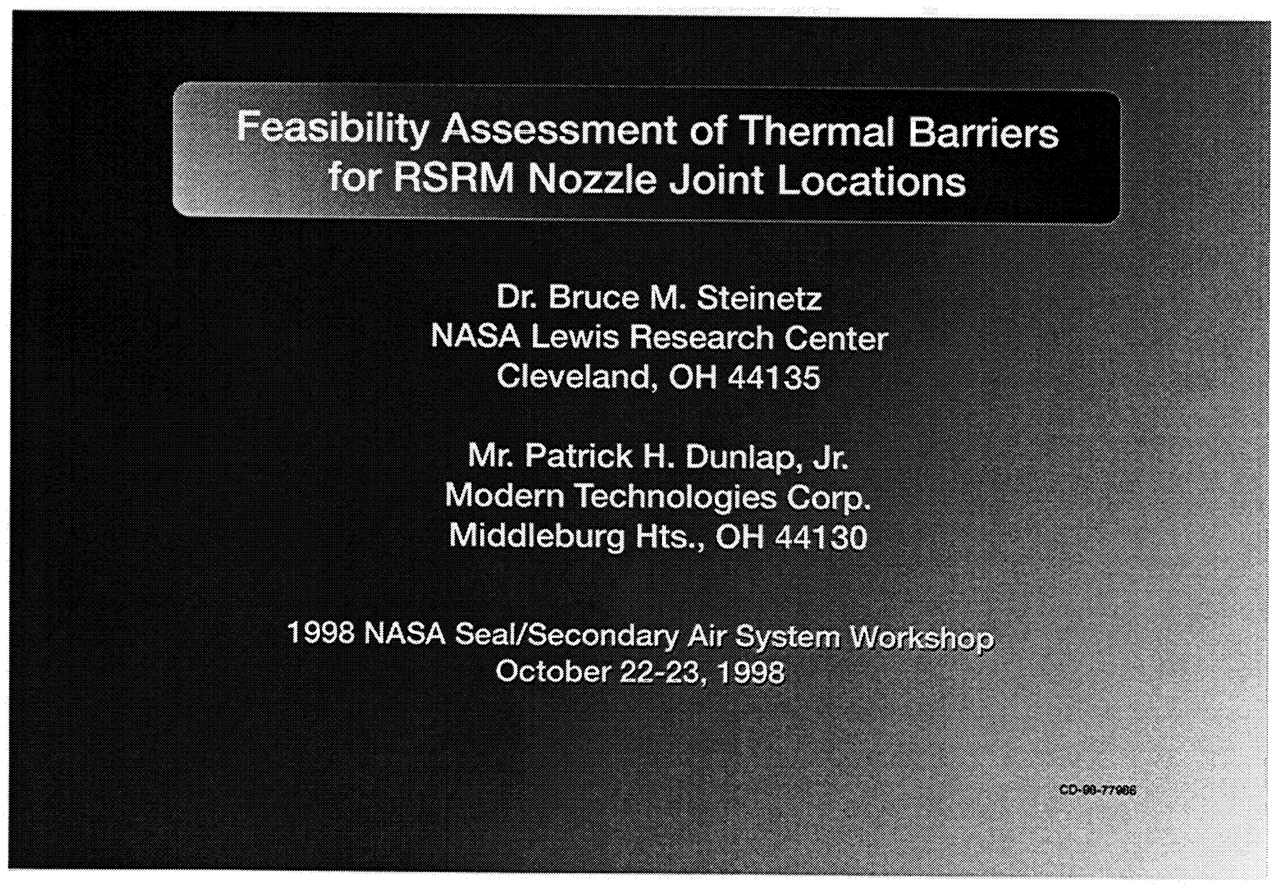


Background

- Solid rockets including the Shuttle solid rocket motor require segment joints for manufacturing and shipment of large elements, propellant cure, motor/nozzle assembly, amongst other reasons.

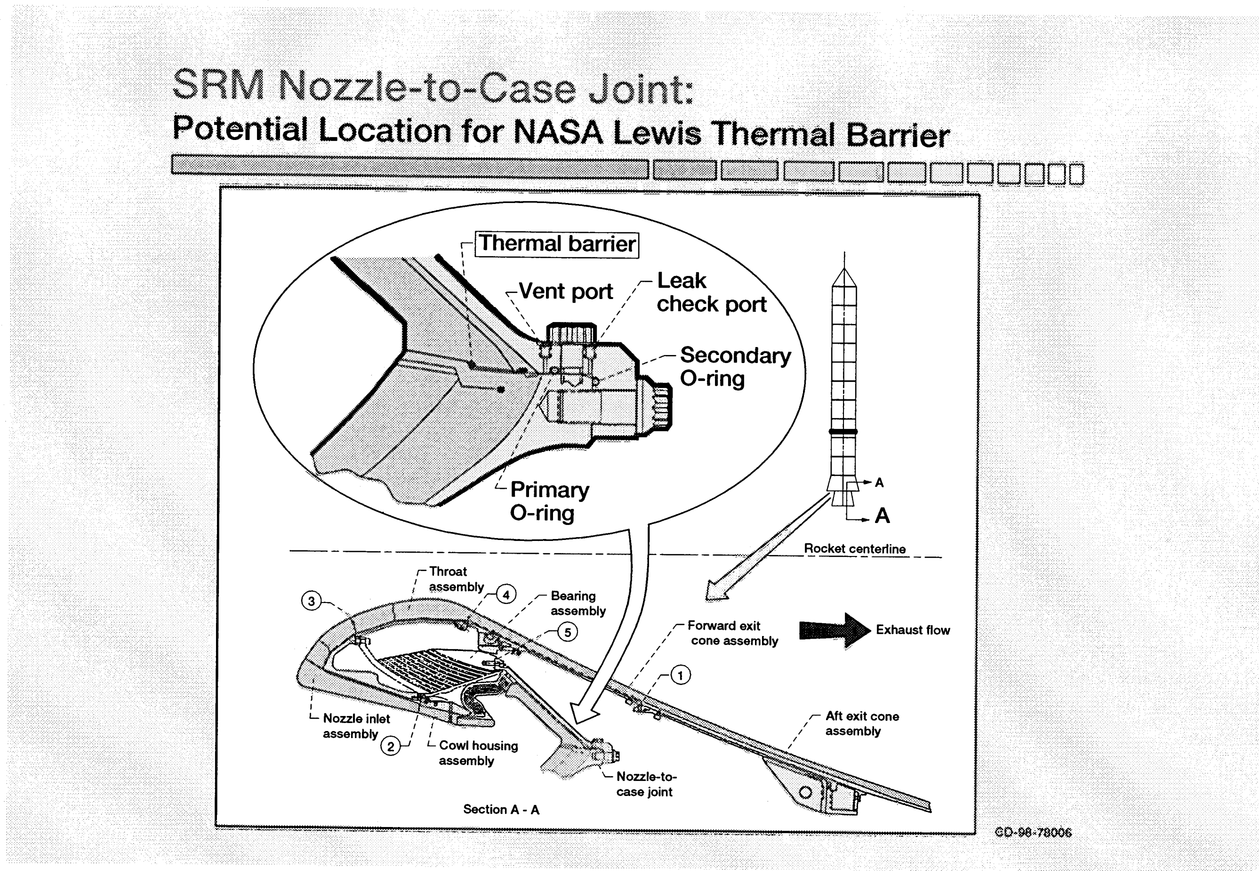
- Segments sealed with primary and secondary O-rings to contain rocket pressures (to 900 psi) and prevent outflow of high temperature (5500°F) combustion gases. Motors insulated with phenolic insulation.

- Inspection of Shuttle nozzle-to-case joints during disassembly revealed *erosion* of primary O-ring seals. NASA and Thiokol Corp. initiated extensive investigation.

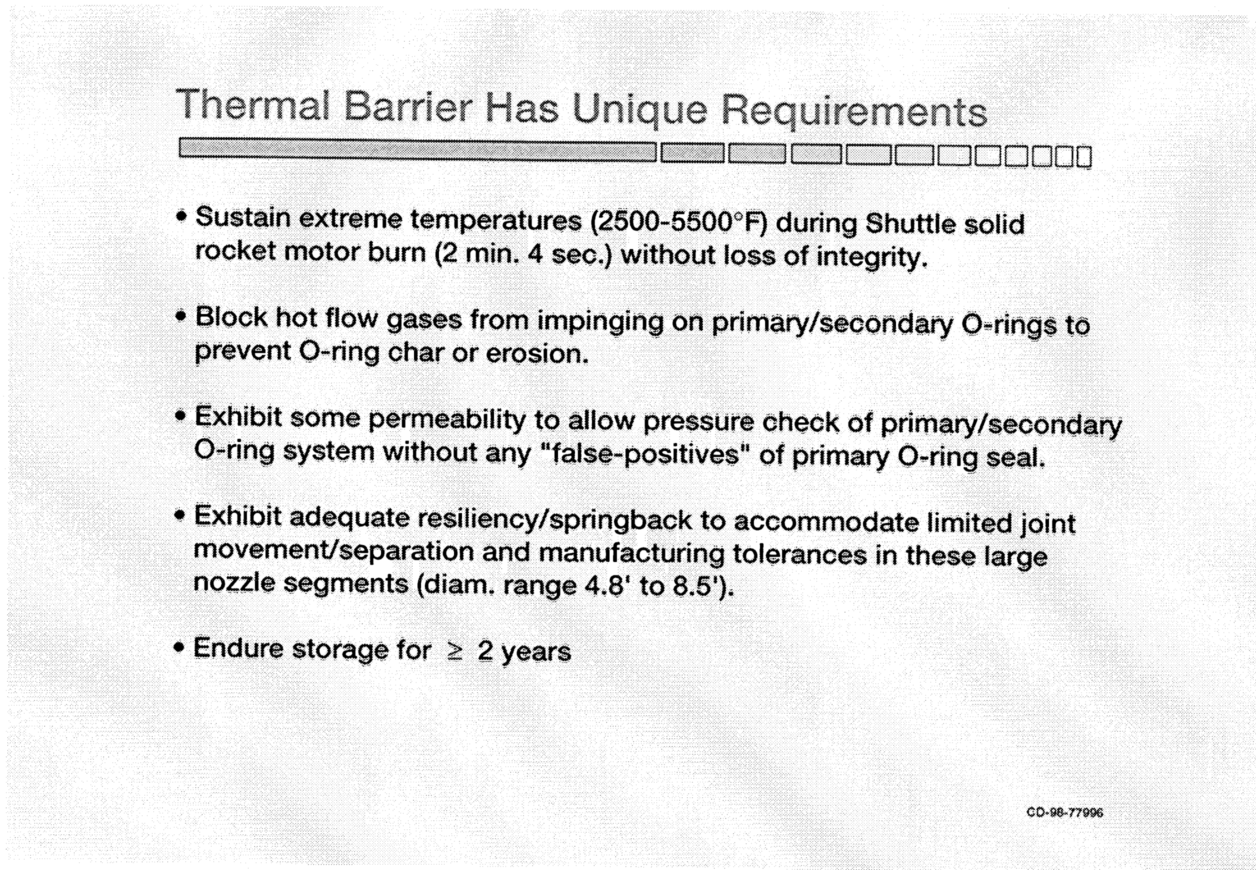
- Thiokol conducted design reviews showing design improvements could be made. NASA Lewis thermal barrier being considered by Thiokol for several nozzle joints (Nozzle-to-case joint and joint Nos. 1-5) based on results described herein.

CD-98-77995

Solid rockets, including the Space Shuttle solid rocket motor, are generally manufactured in large segments which are then shipped to their final destination where they are assembled. These large segments are sealed with a system of primary and secondary O-rings to contain combustion gases inside the rocket which are at pressures of up to 900 psi and temperatures of up to 5500°F. The seals are protected from hot combustion gases by thick layers of phenolic insulation and by joint-filling compounds between these layers. Recently, though, routine inspections of nozzle-to-case joints in the Shuttle solid rocket motors during disassembly revealed erosion of the primary O-rings. Jets of hot gas leaked through gaps in the joint-filling compound between the layers of insulation and impinged on the O-rings. This is not supposed to take place, so NASA and Thiokol, the manufacturer of the rockets, initiated an investigation and found that design improvements could be made in this joint. One such improvement would involve using NASA Lewis braided thermal barriers as another level of protection for the O-ring seals against the hot combustion gases.



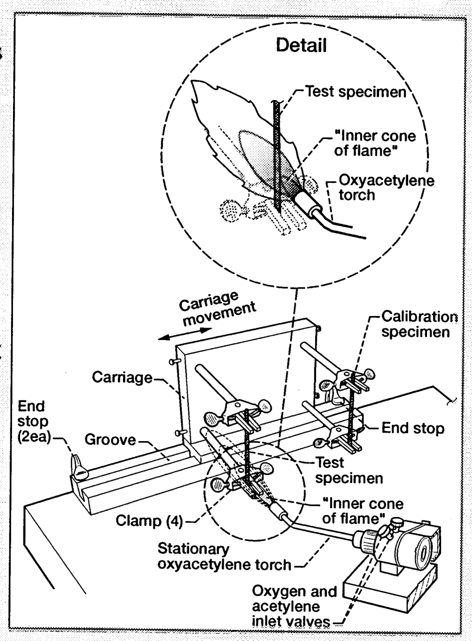
This chart shows where the thermal barrier would be used in the nozzle-to-case joint of the Shuttle solid rocket motor. The figure at the bottom is an enlarged area of the rocket nozzle showing the nozzle-to-case joint as well as nozzle joints one through five. The thermal barrier is also being considered for use in several of these other nozzle joints. The figure at the top is an enlarged view of the nozzle-to-case joint. The primary and secondary O-rings are shown along with the phenolic insulation (in orange) and the surrounding metal hardware (in blue). The thermal barrier is highlighted in its position upstream of the O-rings where it would help block hot combustion gases from reaching the O-rings.



To be used in the nozzle-to-case joint of the Shuttle solid rocket motor, the thermal barrier has several unique requirements. It must be able to withstand extreme temperatures of up to 5500°F during the Shuttle solid rocket motor burn time of 2 minutes 4 seconds without loss of integrity. It must be able to block hot flow gases from impinging on the primary/secondary O-ring system to prevent the O-rings from becoming charred or eroded. However, the thermal barrier still has to be permeable enough to allow a pressure check of the O-rings without any "false-positives" of the primary O-ring. (Refer back to Chart 3) As shown in the schematic of the nozzle-to-case joint, the O-rings are pressurized using a leak check port between them to make sure that they are not damaged and are providing a good seal. If the thermal barrier provided a perfect seal and did not allow some gas to flow through it, it is possible that the primary O-ring could be damaged, but the thermal barrier would seal the joint and make it appear that the primary O-ring was sealing properly. Thus, some gas flow through the thermal barrier is required to prevent this from happening. (Return to Chart 4) The thermal barrier also must exhibit adequate resiliency to accommodate limited joint movement and separation and to make up for manufacturing tolerances in these large nozzle segments which have diameters of 4.8 to 8.5 feet. Finally, the thermal barrier has to be able to endure storage for as long as two years. Once the rockets are assembled, they often sit for several years before they are used.

Burn Test Apparatus and Procedure

- Candidate thermal barrier materials subjected to oxyacetylene torch "neutral" flame (5500°F) temperatures.
- Flame parameters "pre-set" using calibration specimen.
- Carriage fixture ensures consistent location of specimen in hottest part of flame for repeat tests.
- Time for "burn-through" measured for each candidate thermal barrier material.



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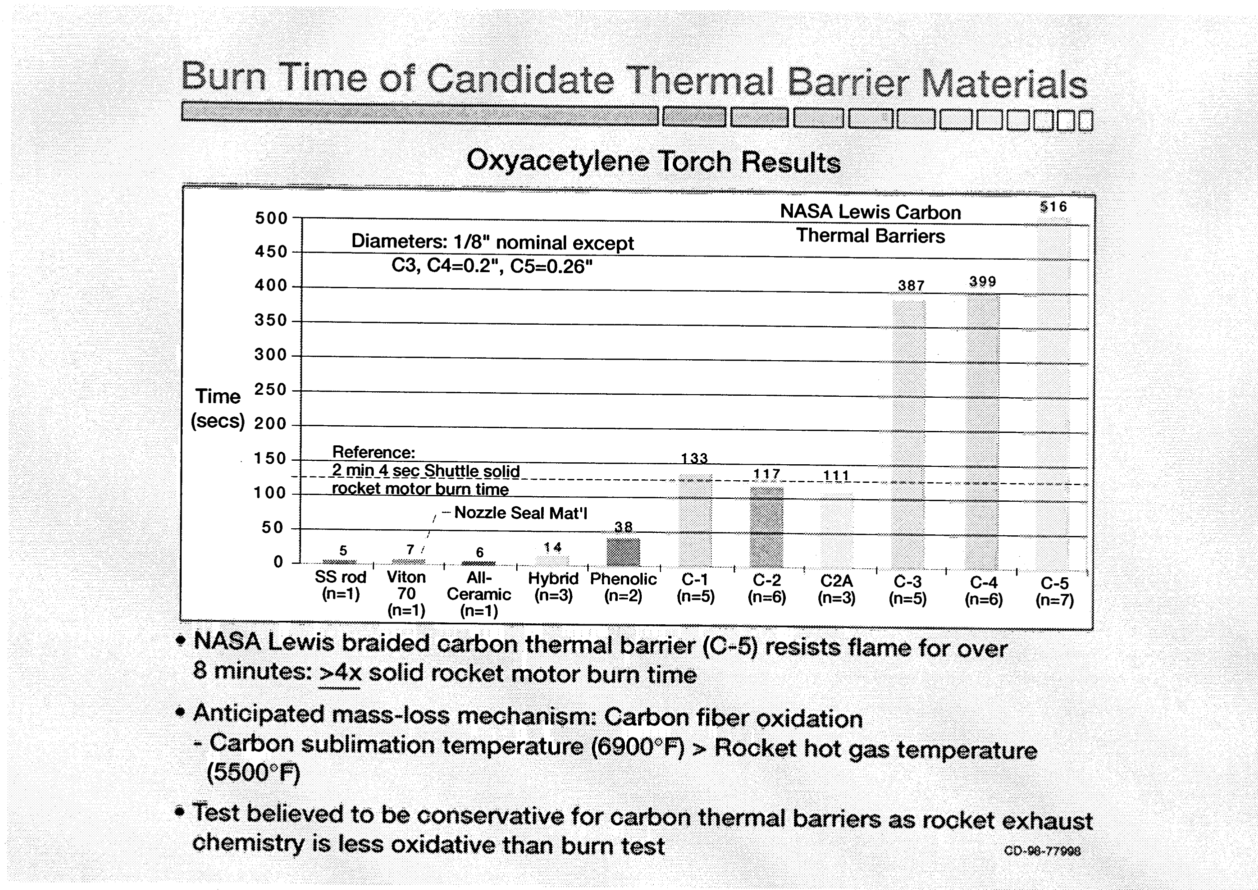
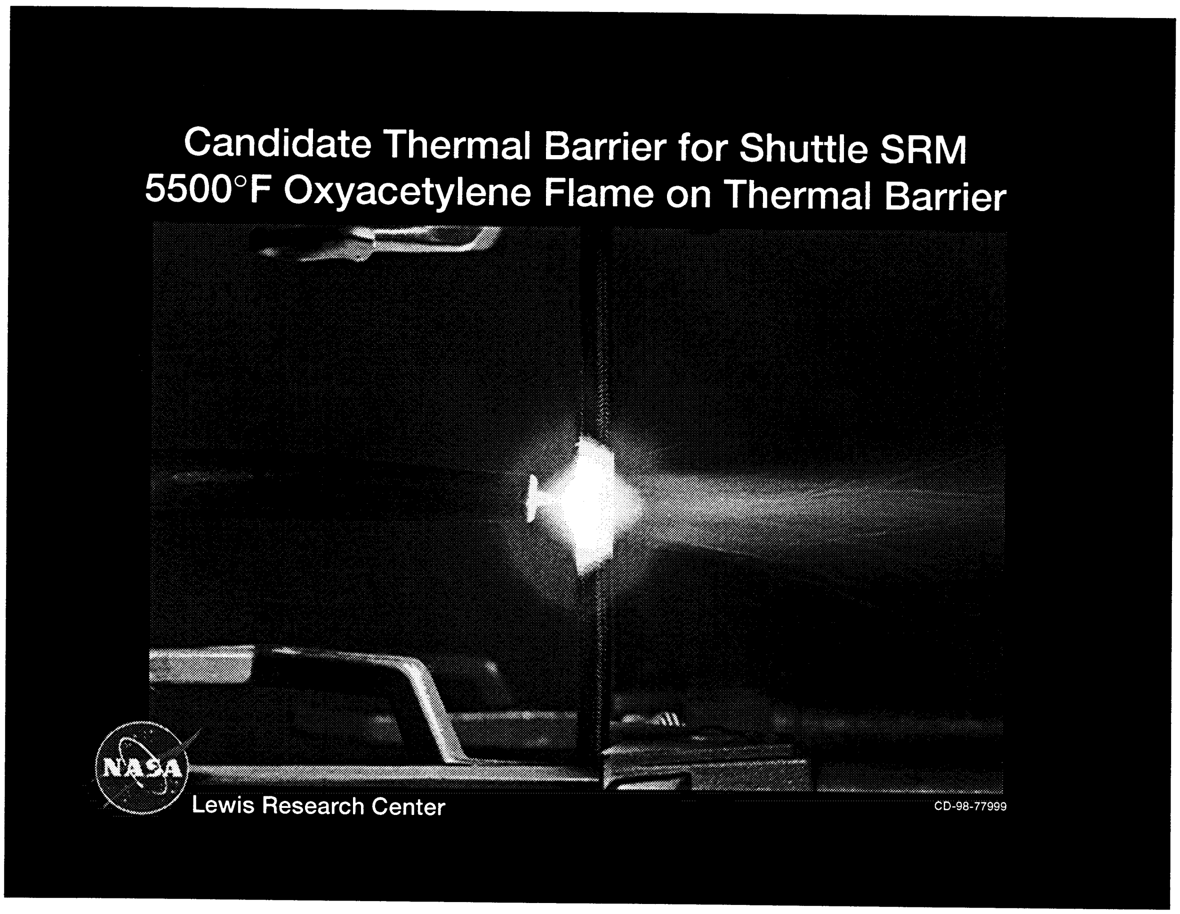
This chart shows a schematic of a simple fixture that we came up with to screen different thermal barrier materials and designs. Candidate materials are placed into the flame of an oxyacetylene torch and the amount of time to completely burn through them is measured. The gas mixture of the flame is adjusted until a neutral flame is formed, and the thermal barrier materials are placed in the hottest part of the flame at the tip of the inner cone where temperatures reach 5500°F. The fixture has a carriage, which can hold both a calibration specimen and a test specimen. The calibration specimen is used to make sure that the flame is adjusted properly and that the specimens are consistently in the hottest part of the flame from test to test. Once it is shown that the flame is adjusted correctly on the calibration specimen, the test specimen is slid into the flame and the amount of time to completely burn through the specimen is measured.

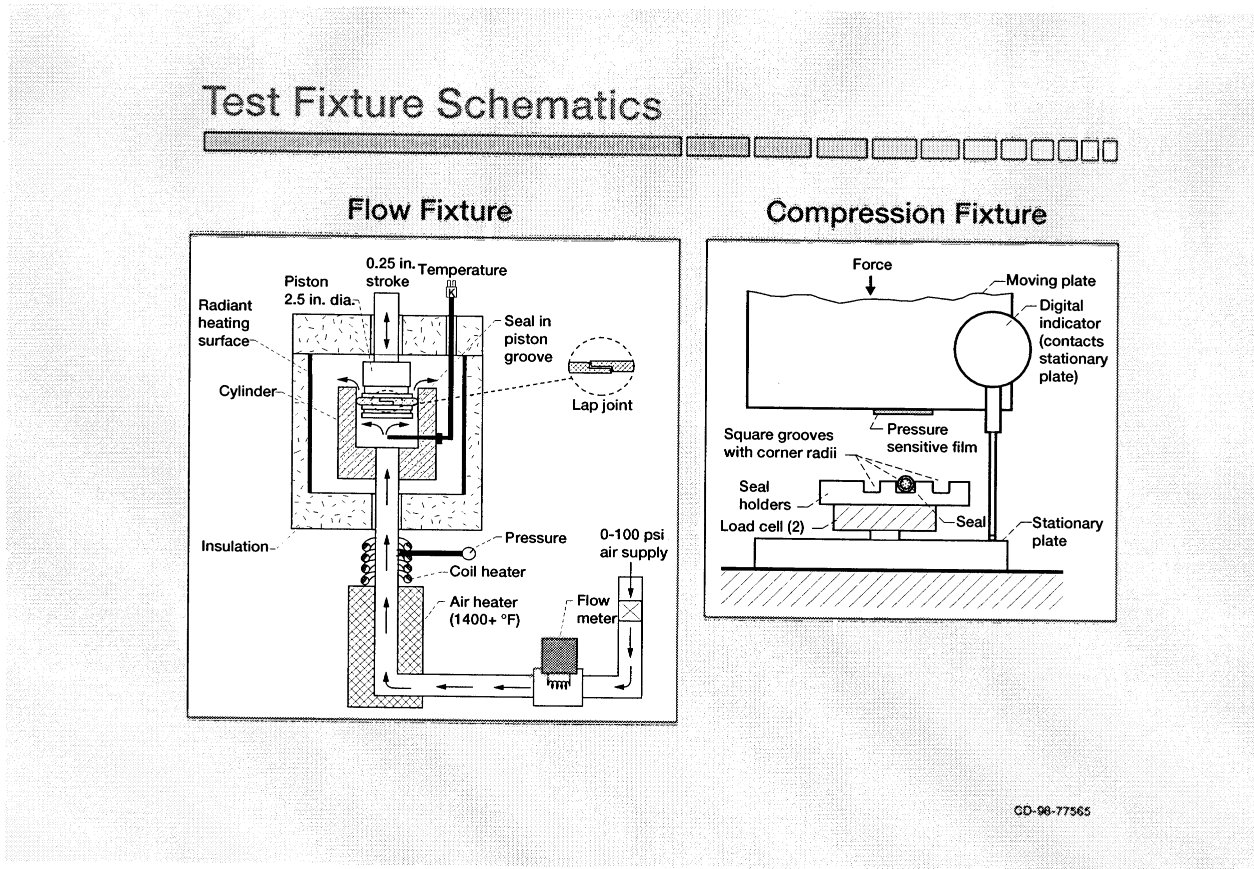


This chart shows the results of burn tests performed on candidate thermal barrier materials and designs. It shows the amount of time that it took for the oxyacetylene torch to cut completely through the different materials. All of the specimens were 1/8" in diameter except the Carbon-3 (C-3) and Carbon-4 (C-4) designs, which were 0.2" in diameter, and the Carbon-5 (C-5) design that was 0.26" in diameter. The first specimen that was tested was an 1/8" diameter stainless steel rod to get a reference point on how hot the flame was. This rod was cut through in only 5 seconds, and the metal was actually melted where the flame cut through. Next, an 1/8" diameter Viton O-ring, the same material used for the O-rings in the rocket nozzle, was tested. It was cut through in about 7 seconds. Two braided rope seal designs were then tested. Like all the other braided rope seal designs, including the thermal barriers, these seals are made up of a core of uniaxial fibers over which layers of sheath material are braided. The all-ceramic design is made up entirely of ceramic fibers, while the hybrid design has a core of ceramic fibers and a sheath braided out of superalloy wires. These designs lasted an average of 6 and 14 seconds, respectively, in the flame. Next, a phenolic thermal barrier was tested that was braided out of phenolic fibers similar to the material used as insulation in the rockets. This material lasted an average of 38 seconds in the flame. Finally, we get to the carbon thermal barriers. The three 1/8" diameter designs all lasted about 2 minutes in the oxyacetylene flame. As a point of comparison again, the Shuttle solid rocket motor burn time of 2 minutes 4 seconds is indicated in the figure. Moving up in diameter, the C-3 and C-4 designs with a diameter of 0.2" lasted about six and a half minutes in the flame. Finally, the 0.26" diameter C-5 design withstood the flame for over 8 minutes, more than four times the solid rocket motor burn time. Thus, the C-5 thermal barrier can endure 5500°F gases for over four times longer than the solid rockets would actually be in operation. After the carbon thermal barriers were removed from the flame, the areas where the flame cut through them were just as soft and flexible as before they were tested. There were no signs

of melting, charring, or embrittlement. We believe that the carbon fibers are actually being oxidized as they are cut through. Carbon fibers oxidize at temperatures above 600 to 900°F depending on the type of fiber. At the other end of the spectrum, the sublimation temperature of carbon is at 6900°F. Therefore, the temperature of the rocket and the oxyacetylene torch at 5500°F is hot enough for oxidation of the fibers but not hot enough for sublimation to occur. Also, these tests are probably conservative in terms of burn resistance because they were performed in an oxidizing ambient atmosphere, whereas the rocket exhaust chemistry is not as oxidative. It is possible that the carbon thermal barriers could be exposed to rocket exhaust in the Shuttle solid rocket motors and not even be effected.

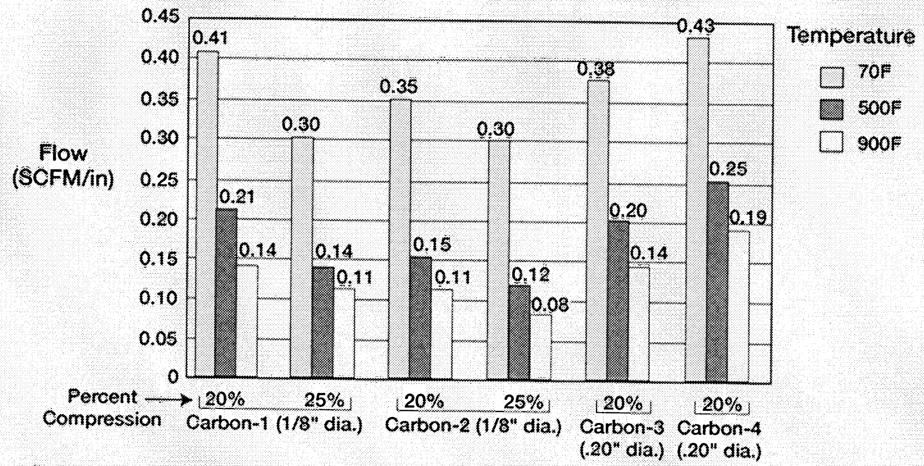


This chart shows the thermal barrier while it is being exposed to the oxyacetylene torch. An incandescent fireball can be seen around the thermal barrier, which is positioned at the tip of the inner cone of the flame. In actuality, this fireball is too bright to look at with the naked eye, and welding glasses must be used to view the test. However, this image was taken with a digital camera that filtered out the brightness of the flame.



The next two schematics are for two more of our test fixtures, the flow fixture and the compression fixture. In the flow fixture seals and thermal barriers are installed into a groove in a piston which is then lowered into a cylinder. Hot, pressurized air is forced into the bottom of the cylinder, and the amount of flow past the seal is measured at different pressures and temperatures. The seals and thermal barriers are installed in the piston by forming a lap joint between their two ends, and the joint is oriented to minimize leakage through the two ends. The other figure shows the compression fixture which is used to determine the loading characteristics of different seal and thermal barrier designs. Seals are inserted into a machined groove, and an opposing plate is moved so that the seal is compressed against this plate. Load versus displacement curves can then be generated. When the seals are unloaded, the amount of resiliency and permanent deformation are measured. The contact area of the seals is also measured by using pressure sensitive film. The film changes color when it is loaded, and the contact area is measured as the area of the film that changed color when the seal was pressed against it.

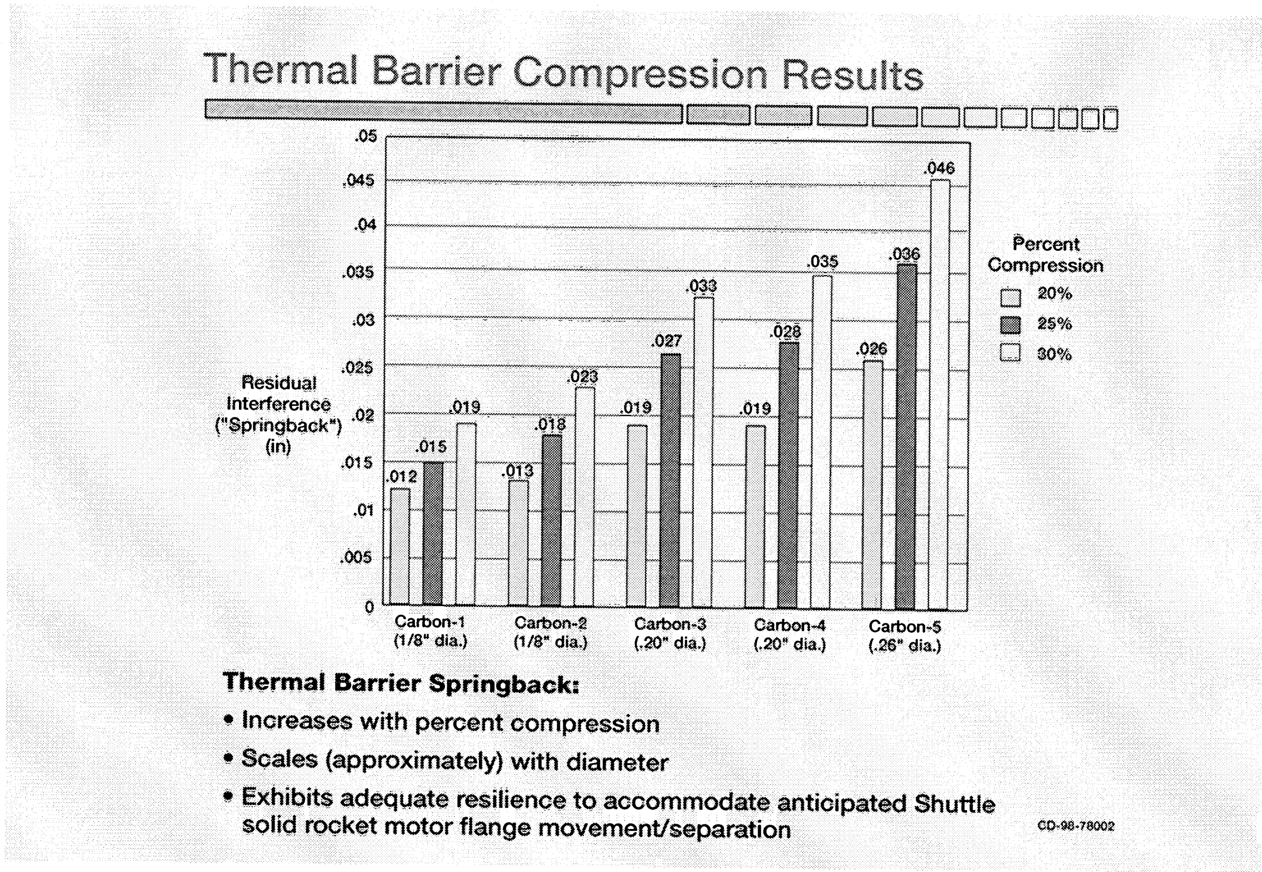
Thermal Barrier Flow Results



- Flow resistance increases with higher compression.
- Mass flow less at higher temperatures because viscosity is higher.
- C-4 (larger diameter core fibers) results in roughly 20% greater flow than C-3.
- Braided thermal barrier exhibits satisfactory flow:
  - Low enough to drop temperature through thermal barrier
  - High enough to permit primary/secondary O-ring leak check without "false-positives"

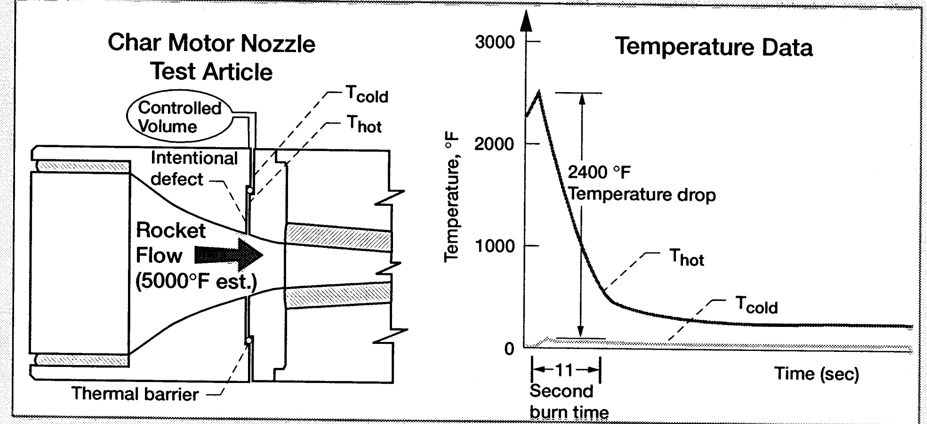
CD-98-78003

This chart shows the results of flow tests performed on the different thermal barrier designs. The figure shows flow rates in SCFM/in at a pressure of 60 psid at different compression levels on the thermal barriers. It can be seen that flow resistance increases with higher levels of compression. When the amount of linear compression was increased from 20% to 25% in the Carbon-1 and Carbon-2 designs, flow rates past the thermal barriers decreased. Also shown in this figure is that mass flow decreased as the temperature increased. At higher temperatures, air viscosity increases, so the amount of flow past the thermal barriers decreases. Overall, the braided thermal barriers restrict flow enough to drop temperatures across them, which will be elaborated on shortly, but are permeable enough to permit leak checks of the primary/secondary O-ring system without any false-positives.



This figure shows results of compression tests performed on the different thermal barrier designs. For each thermal barrier design, the amount of residual interference, or springback, is shown at 20%, 25%, and 30% linear compression. To define springback, use the 20% compression test of Carbon-3 as an example. A 20% compression of this 0.2" diameter thermal barrier means that it is compressed 0.040". For this amount of compression, the thermal barrier "springs back" and recovers 0.019". Thus, there is some permanent set for the thermal barriers when they are compressed. As shown in the figure, the amount of springback increases with percent compression and scales approximately with diameter. Overall, the thermal barriers exhibit adequate resilience to accommodate anticipated movements and separation of the Shuttle solid rocket motor flanges.

Thiokol Char Motor Test Results – Controlled Volume



- Char motor test with intentional joint defect allows hot rocket gas to impinge on thermal barrier for temperature and material performance evaluation
- Results: Thermal barrier provided huge temperature drop:
  - 2500+°F hot side; 100°F cold side: 2400°F delta T through diameter (Generation I 0.125" dia. thermal barrier). Larger diameters planned
  - No apparent burning of thermal barrier
- Char motor tests qualify thermal barrier for subsequent detailed test/evaluation

CD-98-78001

Thiokol, who NASA Lewis is working with to develop the thermal barrier, has performed tests in a subscale rocket "char motor" in which the thermal barrier is exposed to hot rocket gases. The figure on the left shows how the hot gases would move through an intentional joint defect and impinge on the thermal barrier. Pressures and temperatures were measured both upstream and downstream of the thermal barrier. The plot on the right shows temperature traces from a test performed with an 1/8" diameter thermal barrier in the char motor. The plot shows that temperatures on the hot side of the thermal barrier reached 2500°F for an eleven-second rocket firing, while cold side temperatures only reached about 100°F for a 2400°F temperature drop across the thermal barrier. When the specimen was removed from the char motor, it was in excellent condition with no apparent burning or charring. This test qualified the thermal barrier for subsequent detailed testing and evaluation.

Thermal Barrier Development Program – NASA LeRC

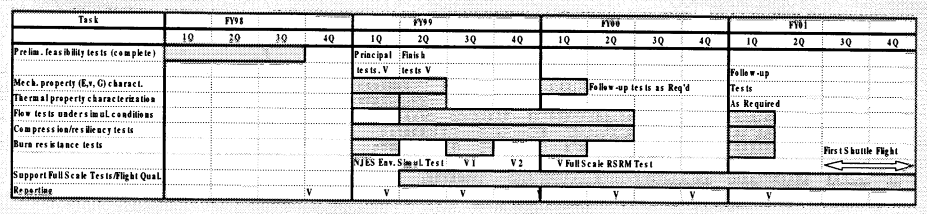
Objective:

Assist Thiokol in maturing the NASA Lewis thermal barrier to RSRM operational status.

Approach:

- Assist in defining optimum thermal barrier config. (architecture, joining, etc.)
- Characterize thermal barrier thermal (Cp, k) properties & mech (E, ϖ, G) properties
- Perform flow, burn-resistance, and compression ("spring-back") tests of the thermal barrier under various conditions
- Consult with Thiokol for preliminary /detailed design phases and for Full Scale RSRM rocket tests, flight qualification, and introduction to service.

Program:



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This chart summarizes the thermal barrier development program in which NASA Lewis will assist Thiokol in maturing the thermal barrier to RSRM operational status. Over the next several years, NASA Lewis plans to assist in defining an optimum thermal barrier configuration by performing additional testing and material characterization on the thermal barrier. Thermal properties, such as heat capacity, conductivity, and coefficient of thermal expansion, and mechanical properties, including elastic modulus, Poisson's ratio, and ultimate strength, will all be determined. Additional flow, resiliency, and burn-resistance tests are also planned. NASA Lewis plans to consult with Thiokol throughout the design phases and through flight qualification and full scale RSRM rocket tests until the thermal barrier is ready for introduction to service. The figure at the bottom shows the proposed development schedule, including a full scale RSRM test and the first planned Shuttle flight using the thermal barrier.

Video:

A video was shown to highlight the burn resistance of the thermal barrier. After showing a 1/8" diameter stainless steel rod being cut through in only 5 seconds, portions of burn tests on Carbon-1 and Carbon-3 thermal barriers were shown. The 1/8" diameter Carbon-1 thermal barrier was cut through in about 2 minutes 30 seconds, while the 0.2" diameter Carbon-3 design took over 6 minutes to be cut through by an oxyacetylene torch.

Summary and Conclusions

- NASA Lewis 0.26" diameter thermal barrier resists 5500°F flame for 8 min. 36 sec. before burn-through:
  - Lasted ≥4X Shuttle solid rocket motor burn-time.
  - Anticipated mass-loss mechanism: Carbon oxidation
- Thermal barrier remains flexible even in hottest burn zone.
- Braided thermal barrier
  - Blocks hot gas flow but permits primary/secondary O-ring leak check
  - Exhibits adequate resilience to accommodate SRM flange movement
- Char motor tests under simulated rocket environment showed thermal barrier provided 2400°F temperature drop through 1/8" diameter thermal barrier.

Thermal barrier feasibility established qualifying it for comprehensive evaluation

CD-98-78004

In summary, the NASA Lewis thermal barrier has shown great promise for use in RSRM nozzle joint locations. The 0.26" diameter thermal barrier has shown the ability to resist the 5500°F flame of an oxyacetylene torch for over eight and a half minutes, more than four times the burn time of the Shuttle solid rocket motors. It is believed that the actual mass-loss mechanism involved in this process is oxidation of the carbon fibers that make up the thermal barrier. After the thermal barrier has been cut through, it remains flexible even in the hottest burn zone with no signs of charring or melting. The thermal barrier blocks hot gas flow well enough to drop gas temperatures across the barrier but is still permeable enough to permit a leak check of the primary and secondary O-rings in the nozzle-to-case joint of the solid rocket motors. It also exhibits adequate resilience to accommodate RSRM flange movements. Char motor tests performed by Thiokol under a simulated rocket environment showed that an 1/8" diameter thermal barrier provided a 2400°F temperature drop across the thermal barrier. In conclusion, thermal barrier feasibility has been established qualifying it for comprehensive evaluation.

TRIBOLOGICAL TUFT TESTING OF CANDIDATE BRUSH SEAL MATERIALS

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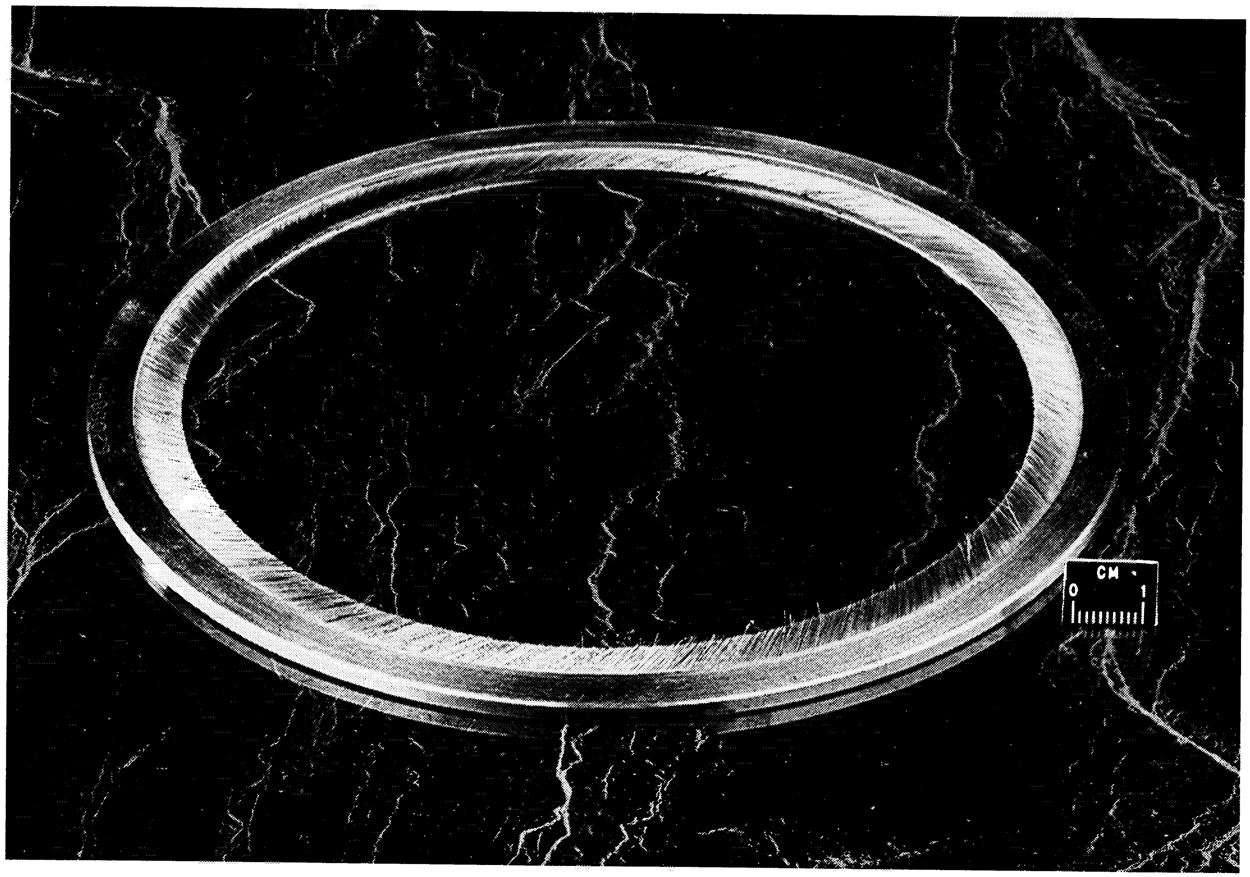
Research Goals

- Develop test method to tribologically brush seal materials
- Evaluate materials to identify potential improvements and trends
- Guide seal material development and selection

CD-98-77931

Turbine Engine Brush Seal



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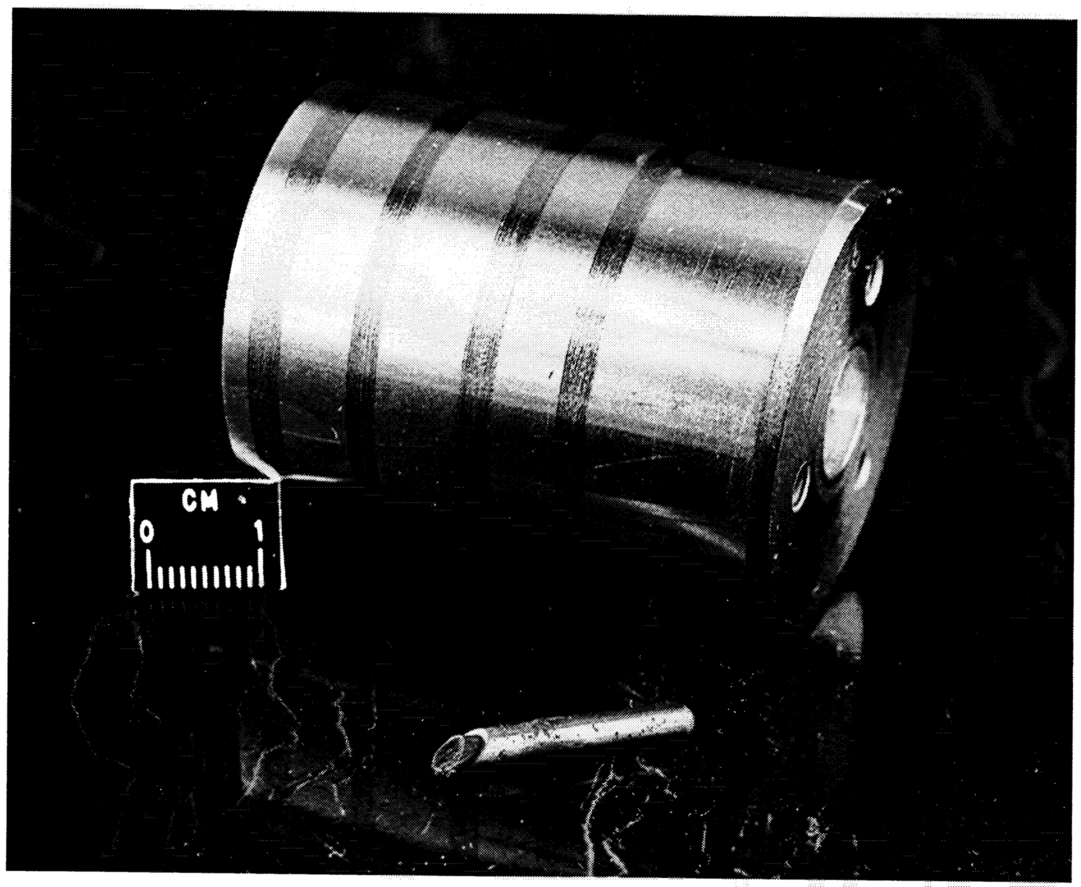
Photograph of typical brush seal

Brush Seal Simulation Specimens



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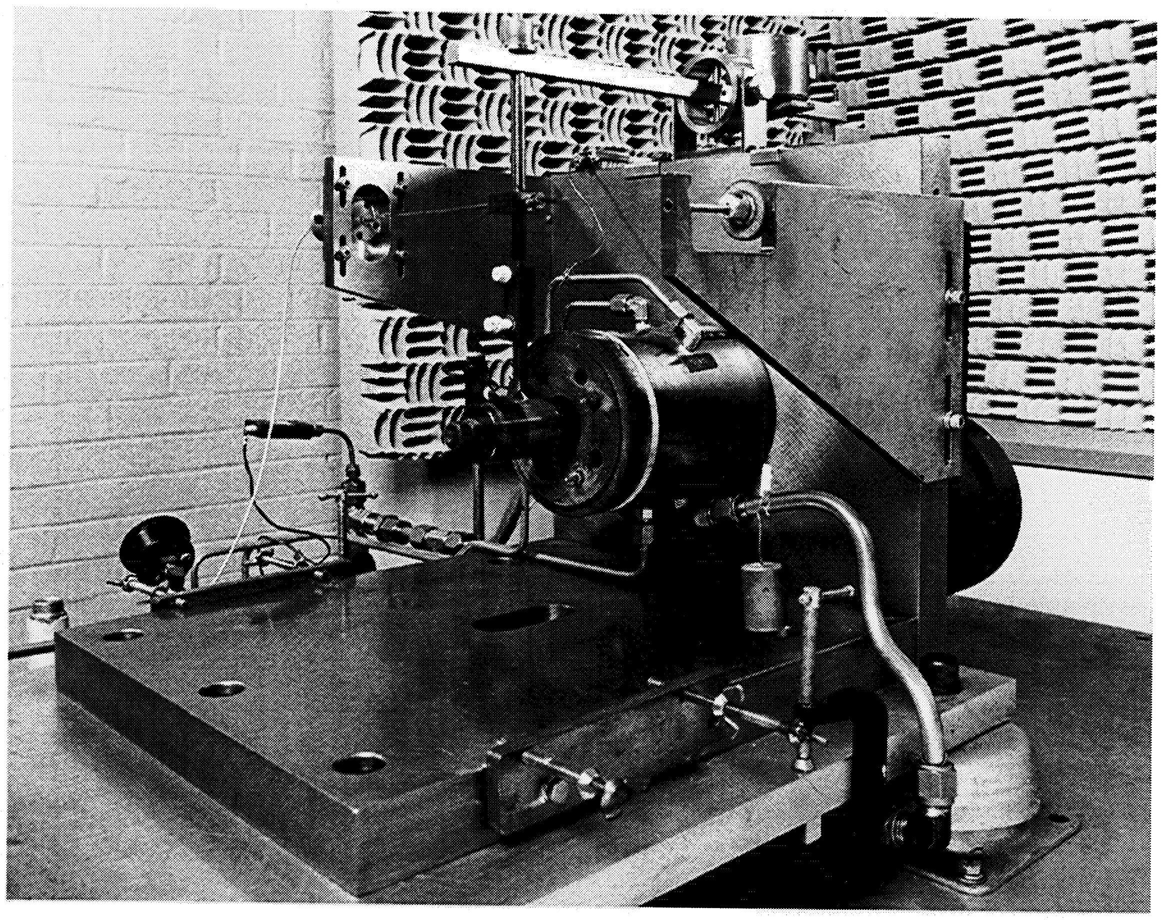
Tuft (lower) and journal (upper) specimens used to simulate brush seal/shaft sliding contact. Note that tuft wears groove into shaft surface.

Brush Seal Tuft Test Rig



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Photograph of high temperature (1400°F) tuft test rig showing specimen arrangement for testing.

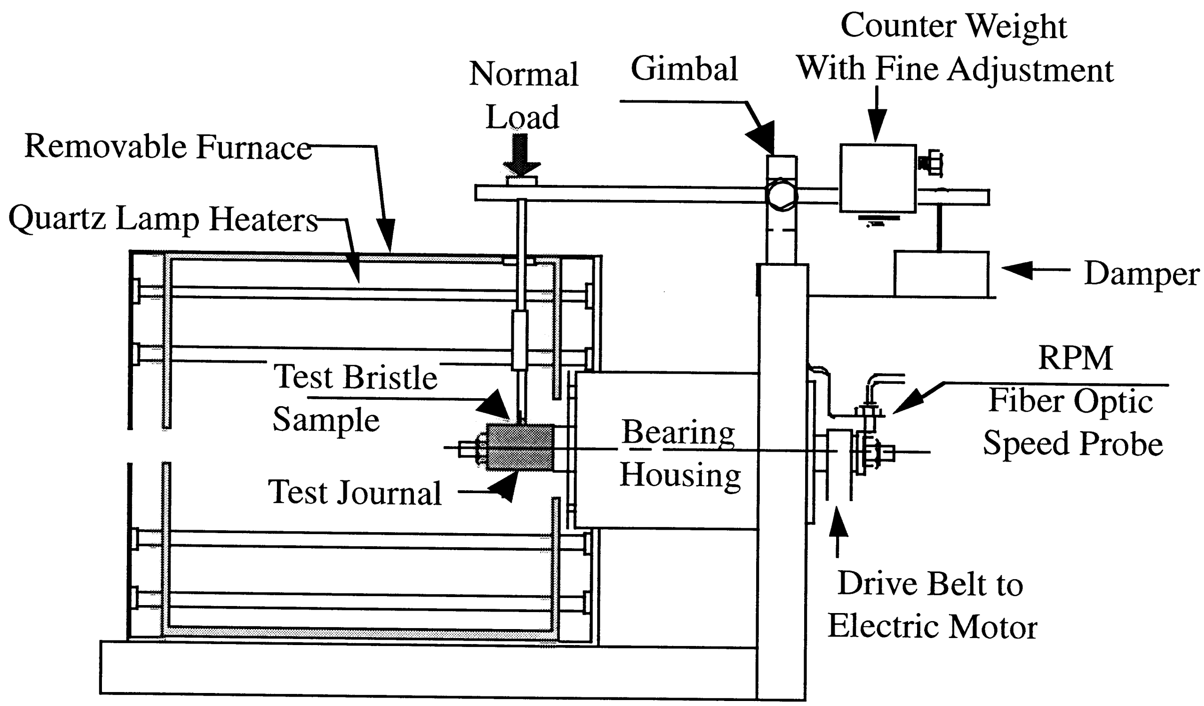
Comparison of Simulation to Seal

Characteristic	Brush Seal	Tuft Test
Loads	0-20 psi (variable)	1-20 psi (constant)
Speeds	≈ 1000 ft/sec	≈ 100 ft/sec
Temperatures	75 - 1200°F +	75 - 1400°F +
Tribological	?	Friction Forces Wear Data

CD-98-77935

The tuft test can simulate most of the sliding conditions encountered by brush seals. In addition, friction and wear can be easily measured.

Schematic of Tuft Test Rig



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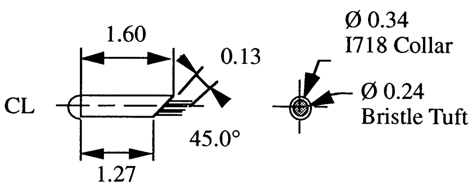
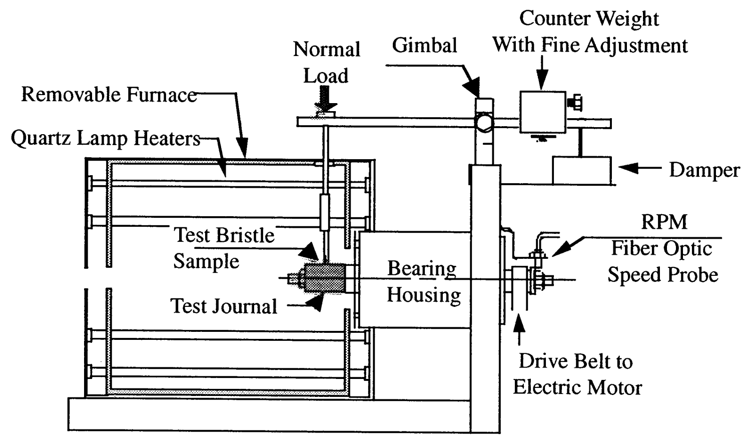
Test Specimens

Tuft



Journal



CD-98-77937

Tuft sample is made by packing 960 wires into an Inconel collar. The wires are held in place by welding followed by grinding of the tuft surface to a 45° angle.

Brush Specimen Configuration

Chemical Composition of Wire Samples (wt.%)

	Co	Ni	Cr	Fe	W	Mo	OTHERS (< 6 wt.%)
H25	51	10	20	3	15	—	Mn, Si, C
I718	—	52.5	19	18.5	—	3	Nb, Ti, Al, C, Cu
H230	5	52.7	22	3	14	2	Si, Mn, C, Al, B, La
H242	2.5	60	8	2	—	25	Mn, Cu, Al, Si, C, B

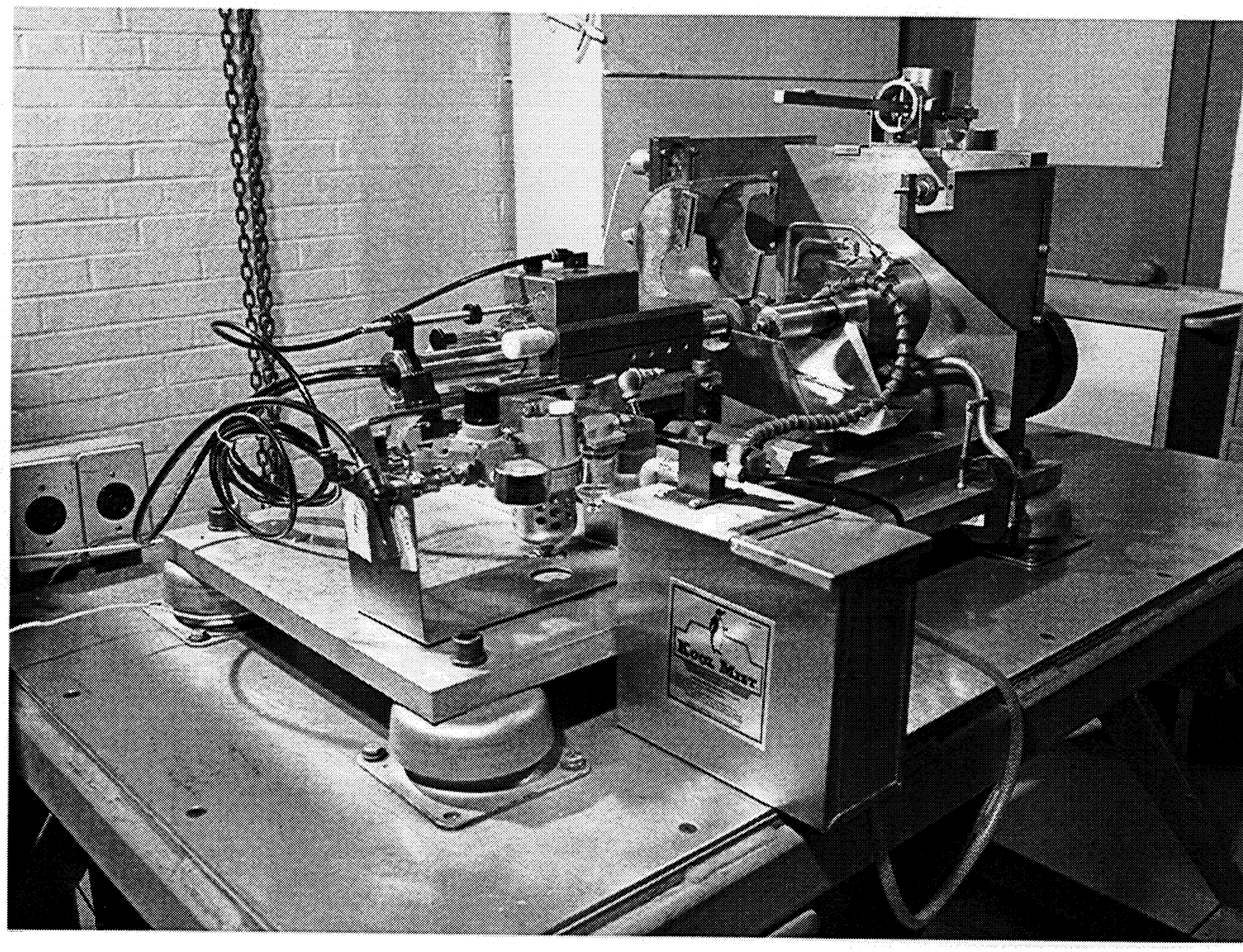
CD-98-77938

Operational Issues

- Vibrations
  - Interfere with accurate data collection and results in variable load
- Solution (s)
  - Add dashpot damper
  - Eliminate run-out using in place grinding system

CD-98-77939

In-place Grinding System



CD-98-77940

With this set-up, as coated journal specimens are mounted to the test rig shaft. In-place grinding, shown here, eliminates run-out and ensures a vibration free test.

Results Review

Testing of Solid Lubricant Coatings

Coating Compositions by Weight and Percent Volume of PS212, PS300, HVOF300

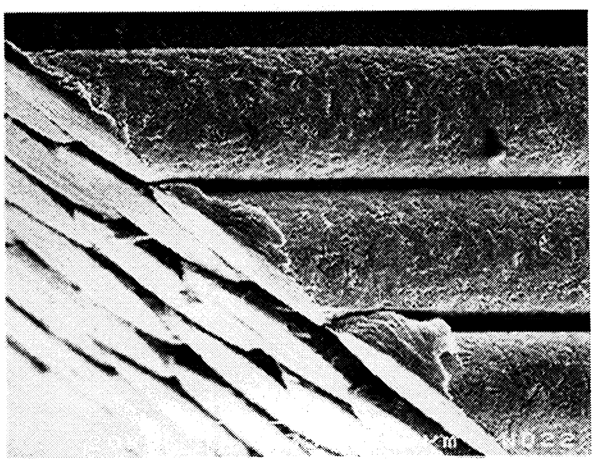
Coating	Constituent, wt.% (vol. %)			
Designation	Ni-Co-Cr_2C_3*	NiCr-Cr_2O_3**	Ag	BaF_2/CaF_2
PS212	70 (67)	—	15 (9)	15 (24)
PS300 and HVOF300	—	80 (80)	10 (6)	10 (14)

* By wt.% contains 54 Cr_2C_3, 28 Ni, 12 Co, 2 Mo, 2 Al, 1 B, and 1 Si
**By wt.% contains 80 Cr_2O_3, 16 Ni, and 4 Cr
refs. 4, 5, and 6

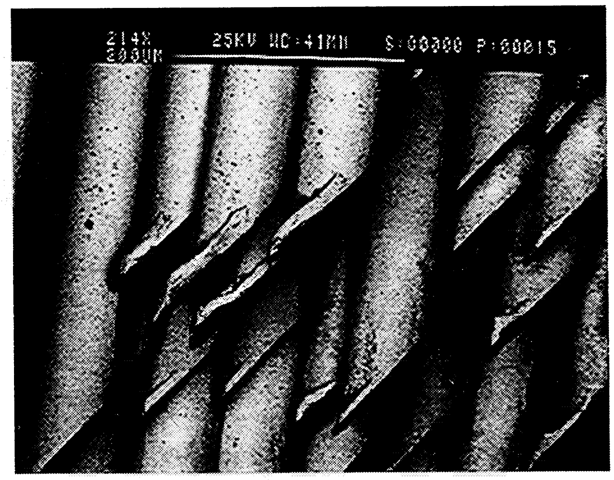
CD-98-77941

Typical Surface Appearance

Tuft Test



Brush Seal

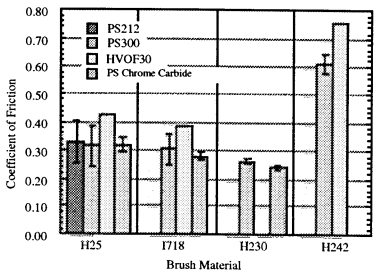


CD-98-77942

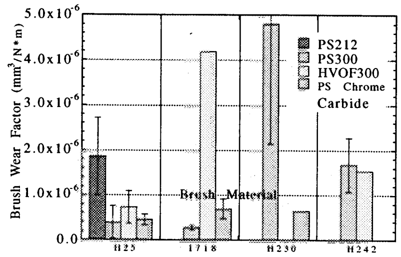
Note that the surface features observed after tuft testing match those seen in brush seals. This lends confidence in the relevance of the tuft results.

Tribological Data (1200°F)

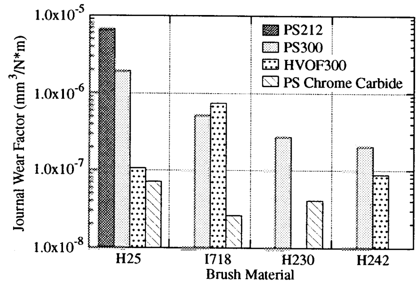
Friction



Brush Wear



Journal Wear



CD-98-77943

Friction and wear data summary shows that the choice of wire material has a significant effect on friction. Journal coating can have a dramatic effect on both brush and journal wear.

Data Summary

- Friction largely unaffected by coatings
- Wear of “standard” materials better than “lubricated” coatings
- Data may be influenced by coating microstructure

CD-98-77944

Summary

- Tuft test excellent screening tool
- Wear data suggests an improvement in 2 + orders of magnitude desired for long life of interference fit
- Tester capable of 1400°F + making it ideal for selection of alternate wire materials (e.g. ceramics)

CD-98-77945

Relevant Publications

"Preliminary Tuft Testing of Metallic Bristles Versus PS212, PS300, and HVOF300"
NASA TM 107522

"High Temperature Brush Seal Tuft Testing of Selected Nickel-Chrome and Colbalt Superalloys"
NASA TM 107497

"A New Tribological Test for Candidate Brush Seal Materials Evaluation"
NASA TM 106753

CD-98-77946

ADVANCED BEARINGS/SEALS FOR GENERAL AVIATION ENGINES

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Mohawk Innovative Technology, Inc.
Albany, New York

Team

NASA:
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MiTi
Heshmat, H., Ph.D.
Salehi, M., Ph.D.

RPI
Blanchet, T., Ph.D.

Williams International

Objectives

Global

Develop Seal, design tools and manufacturing technology
To support NASA, GAP, and Aerospace Industries

Specifically

- Develop preliminary bearings/seals for W.I.GA engine
- Enhance/Expand existing compliant foil, and analysis tools for seals
- Select materials and coatings (commercialization of NASA PS 304 coatings
- Validate analysis through experiments

Compliant Foil Seals

Needs

Consistent function at high temperature and pressure
Wear resistance
Compact & Lightweight

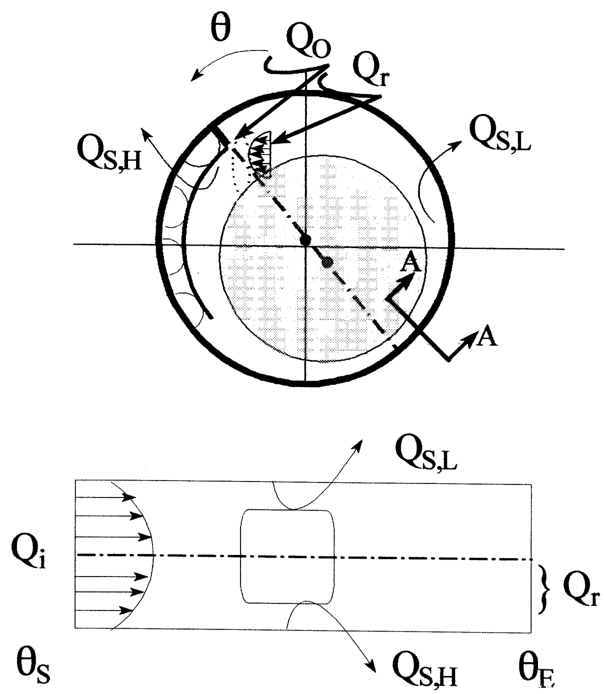
Materials

High Temperature Foil Inco X-750
High Temperature Shaft Coating - NASA PS304

Special Considerations

Thermal Analysis: temperature not to exceed material capabilities
Flow Analysis - Coupled hydrodynamic and compliancy

A Simplified Model for Flow & Thermal Effects in a Foil Bearing



Side Flow

$Q_S \approx Q_{S,L} + Q_{S,H}$

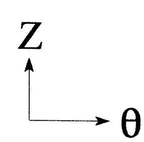
Inlet

$Q_i \approx Q_O + Q_r$

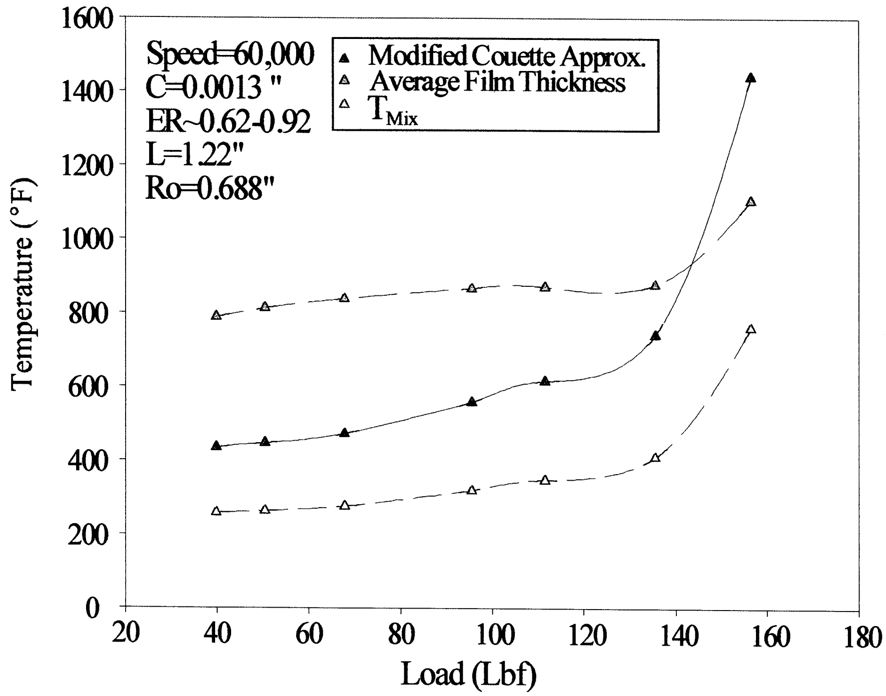
$T_i = f(T_O, T_r)$

Energy Balance Approximation

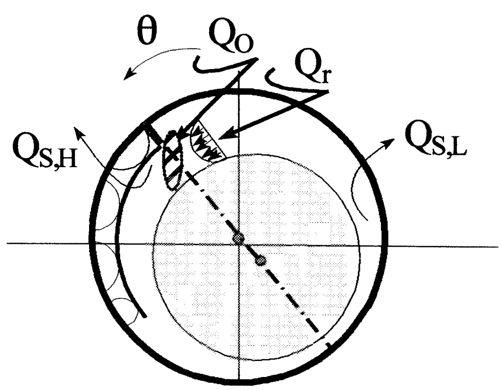
$Q_i\, T_i \approx Q_S\, T_{S,avg} + Q_r\, T_{max,avg}$



Approximate Temperatures from the Analysis of Foil Bearing



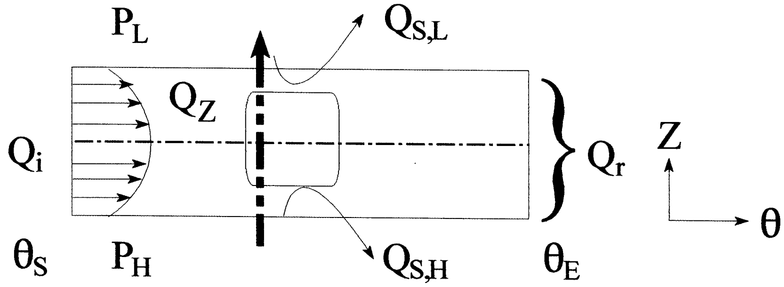
Flow Model in a Seal



Boundary Conditions:

A. Periodic Boundary @ θ_S and θ_E
i.e. Film thickness and presure at the begining and the end of the seal are the same

B. $P@\ z=0 \geq P@z=L$



Governing Equations and Boundary Conditions

Reynolds Equation:

Velocity & Inertia

$$\frac{\partial}{\partial\theta}\left[\bar{P}\,\bar{h}^{3}\frac{\partial\bar{p}}{\partial\theta}\right]+\frac{\partial}{\partial\bar{z}}\left[\bar{P}\,\bar{h}^{3}\frac{\partial\bar{p}}{\partial z}\right]=\Lambda\frac{\partial}{\partial\theta}(\bar{P}\,\bar{h})$$

$\bar{z} = (Z/R)$ $\bar{p} = (P/P_L)$ $\bar{h} = (h/C)$

Film Thickness :

$$\mathbf{h = C + e\,Cos\,(\theta - \theta_0) + \underbrace{\sum K_{ij}\,(p_{eff} - PN)}_{\text{Compliancy}}}$$

K_{ij} : The combined compliancy coefficeint

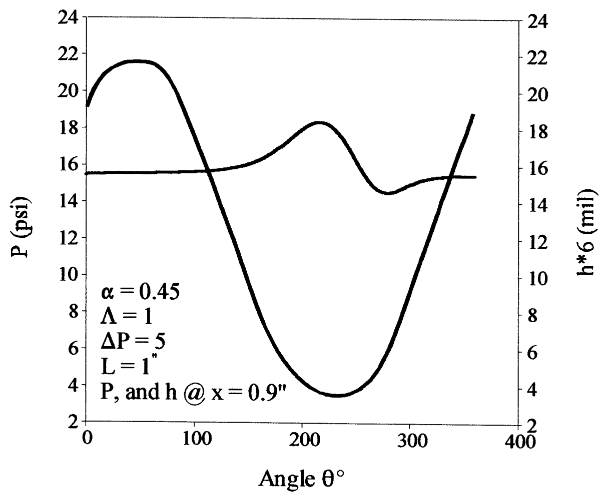
PN: Normalized pressure behind foils

Numerical Approach:

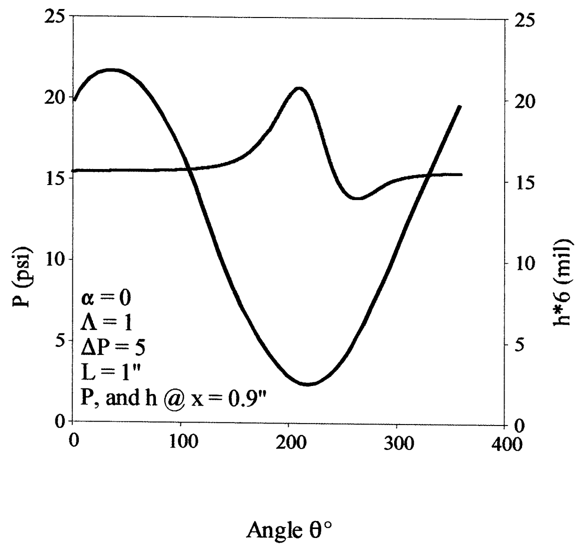
- Pressure and film equations are solved simultaneously
- The numerical method is a combination of successive over-relaxation (SOR) method and the iteration method
- Effect of top foil compliancy is taken into account by considering the neighboring pressure effect in the axial and circumferential direction on the film thickness about a node
- Applying the previous condition allows the top foil to be extensible only in circumferential direction.
- The axial pressure distribution is not imposed, but is determined from the solution of the Reynolds equation

Pressure and Film Thickness Distribution

Compliant Surface



Rigid Surface

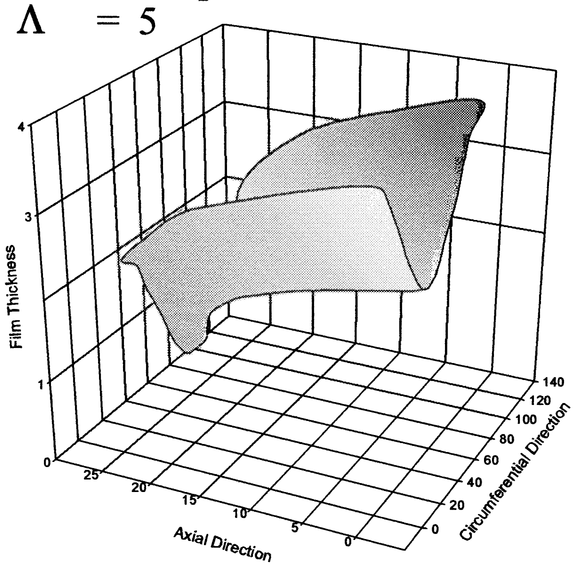


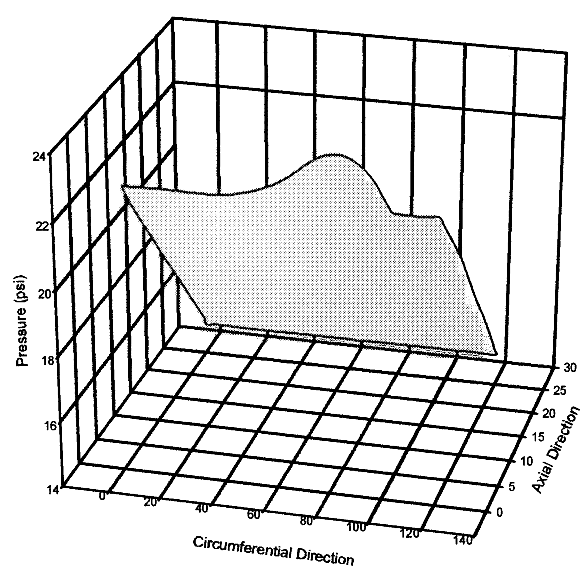
Film Thickness and Pressure Distribution

L/D = 0.5

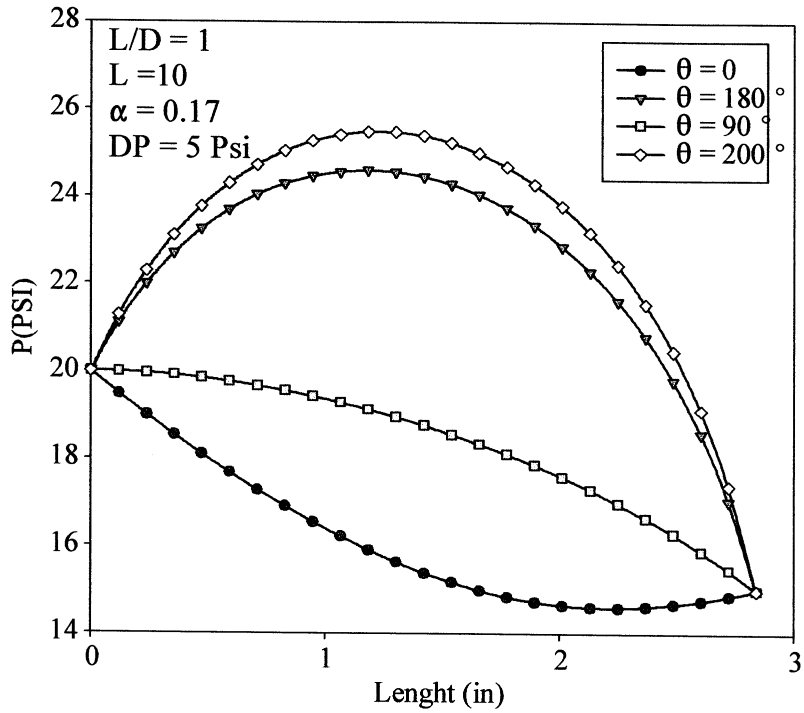
ΔP = 7.5 psi

Λ = 5

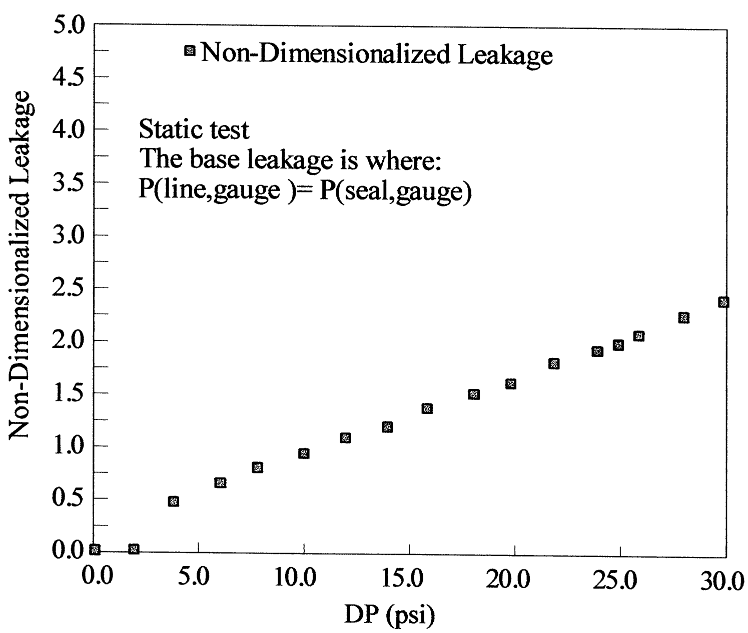




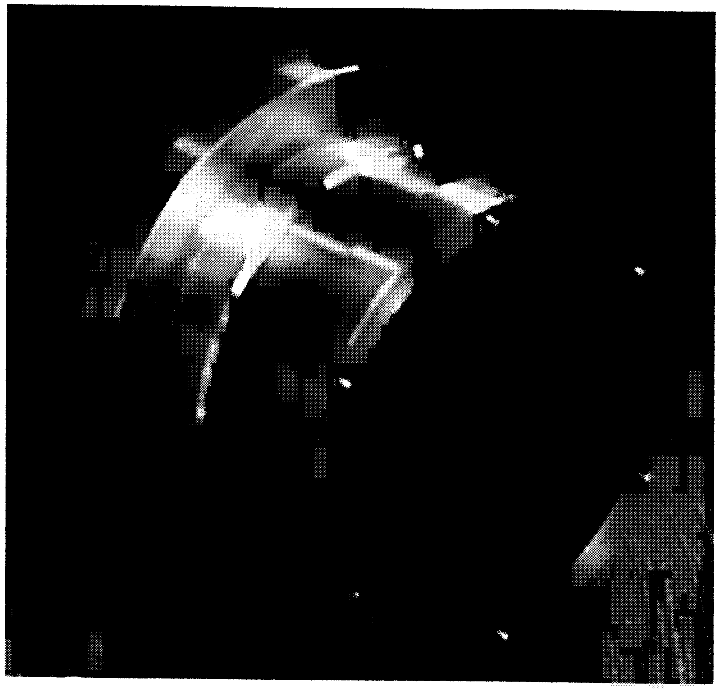
P Distribution Along the Seal at Different Circumferential Position



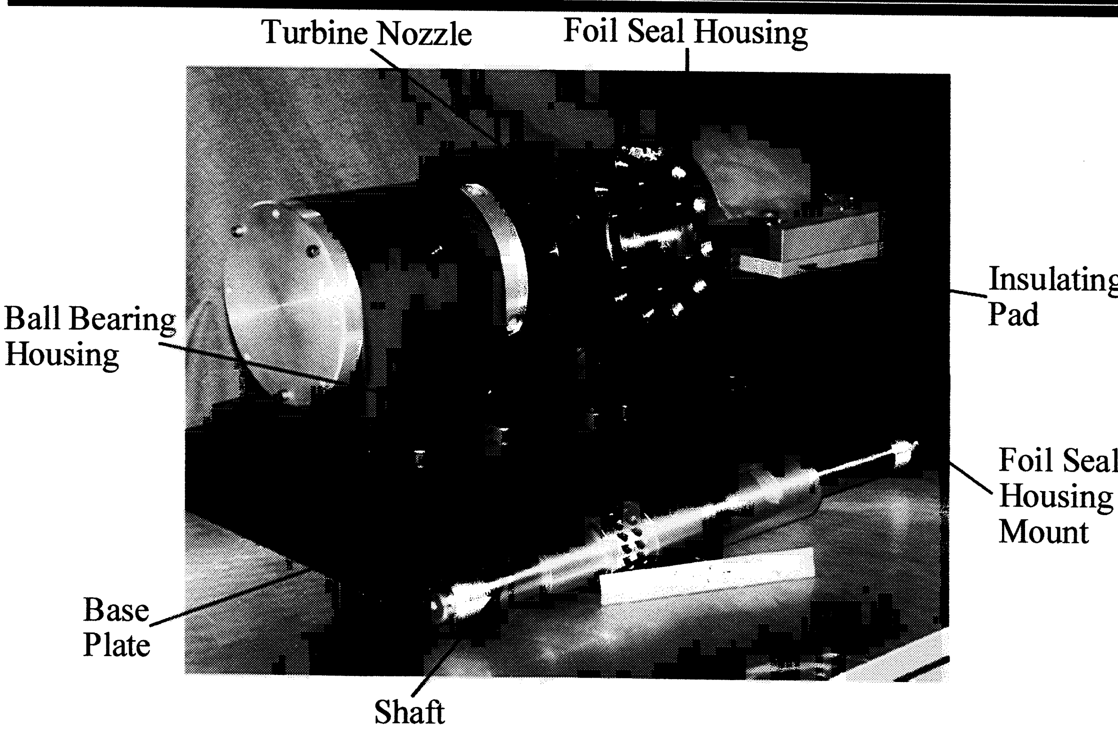
Foil Seal Leakage Test



Prototype Compliant Foil Seal Assembly



Test Apparatus



Progress

- Thermo-Hydrodynamic Coupled Analysis Developed for Foil Bearing and Seals
- Established Numerical Method
  - Reynold's Equation solved with non-symmetric B.C.s & Compliancy
  - The Viscosity-Temperature relationship employed for T_max
  - Pressures and Leakage Flow
- Theoretical/Experimental Comparison
  - Couette Approximation with empericism will provide good estimate of temperatures.
  - Comparison with available measured temperature data provides guide for conduction/convection ratios

Progress - Cont'd

- The overall design of experimental apparatus is completed
- Rig parts being fabricated
- Preliminary Foil Seal Fabricated
  - Addresss manufacturing issues
  - Lift off tests completed and successfully demonstrated
- Lubricant Coating Activities at RPI
  - Plasma Spray Vendors Identified
  - Mods to Tester to Evaluate Integrity of Coating Near Completion
  - Bearing and Seal Journals Fabricated

ROCKET TURBOMACHINERY SEALS

John E. Keba
Boeing/Rocketdyne Propulsion & Power
Canoga Park, California

Rocket Turbomachinery Shaft Seals

- Introduction
- Operating Environments
  - Fluids and fluid conditions
  - Various stages of turbopump operation
- Design Issues
  - Inter-Propellant-Seal (IPS) Systems
  - 'Lift-off' Seal Systems
- Technology Development Needs

Design Issues

- Function
- Safety
- Performance
    - Propellant loss
    - Turbopump efficiency
    - System weight
- Environment -- Physical and Chemical
- Packaging
    - Influence on turbopump configuration
    - External systems
- Life, ‘ilities,* Health Monitioring Systems
- Cost and Schedule

*Jargon for Operability, Maintainability, Reliability, and other similar terms.

Operating Environment

- Fluids
  - Cryogenic: Liquid Oxygen (LOX), Liquid Hydrogen
  - Storable
    - Oxidizers: Nitrogen Tetroxide (NTO), Hydrogen Peroxide
    - Fuels: Kerosene (RP-1), Monomethylhydrazine (MMH)
  - Hot Gas
    - Generally fuel rich
    - Oxygen rich for LOX-RP-1 staged combustion

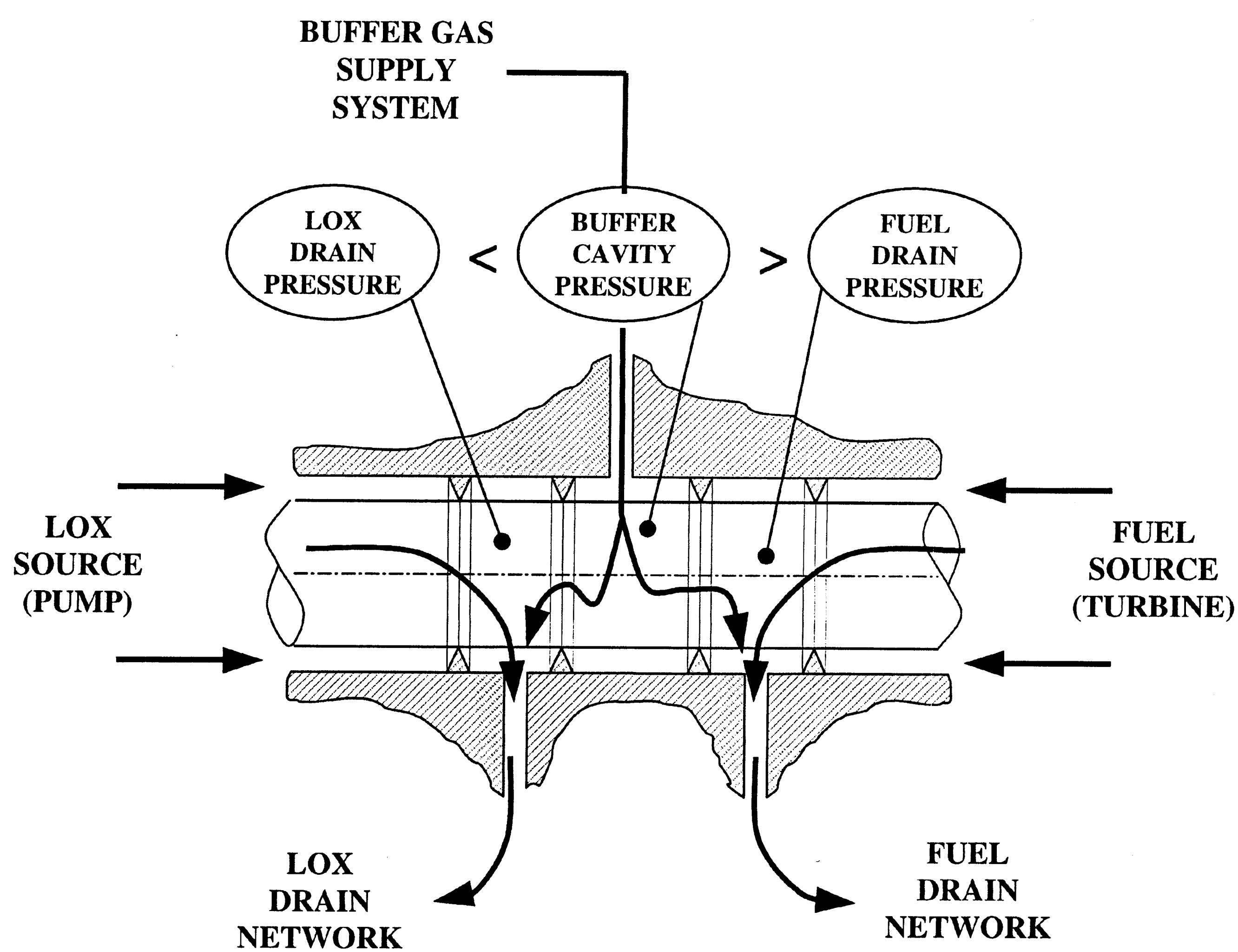
Operating Environment

- Stages of Operation
  - Chilldown
  - Start
  - Operating
  - Shutdown
  - Coast
  - Restart
  - Purge and Secure

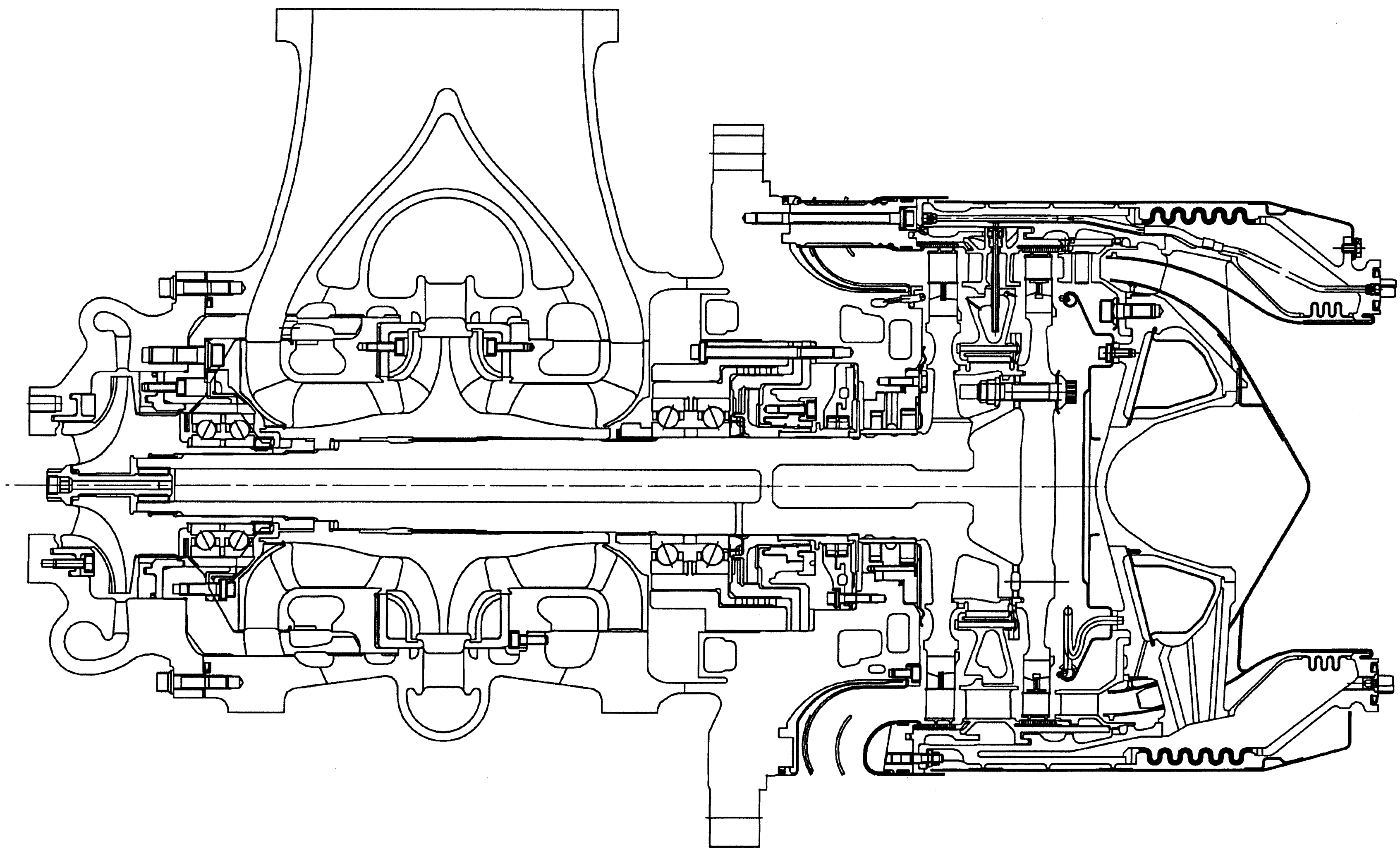
Inter-Propellant-Seal (IPS)

- IPS Purpose
  - Separate incompatible fluids
  - Minimize propellant loss
- IPS Design Requirements
  - Reliable, Robust
  - Use minimal buffer gas
  - Use minimal axial pump length

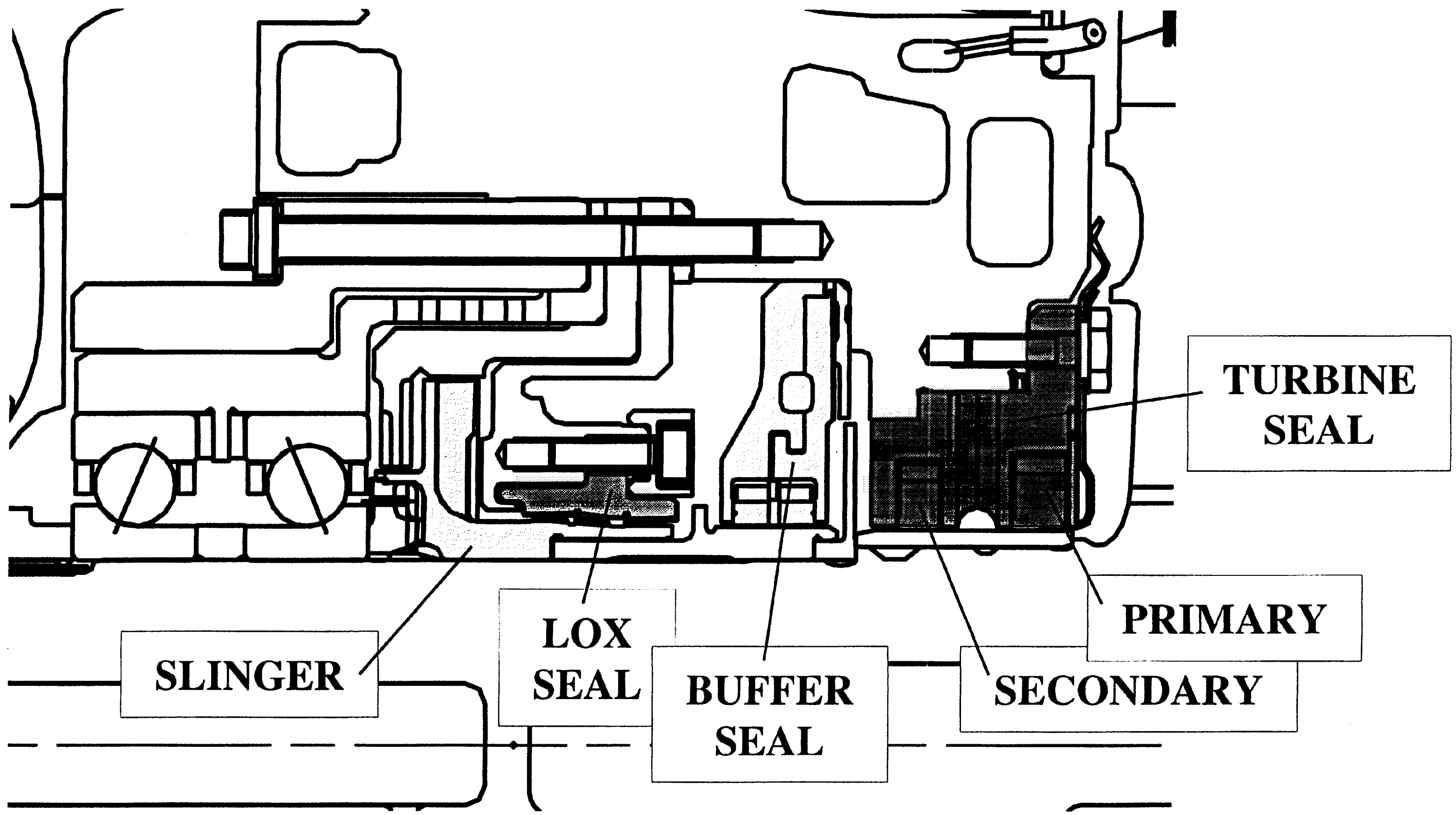
Inter-Propellant Seal System



SSME High Pressure Oxidizer Turbopump



SSME High Pressure Oxidizer Turbopump Inter-Propellant Seal System



Inter-Propellant Seal System Design Considerations

- LOX Source
  - Supply Pressure and Temperature
    - Slinger (throttling, power)
    - Vent to pump inlet (suction performance, additional seal, porting

- Fuel Source
  - Hot Gas
    - Staged seals
    - Transient thermal environment
  - Liquid (bearing sump or single shaft arrangement)
    - Inerting during chill, shutdown

Inter-Propellant Seal System Design Considerations

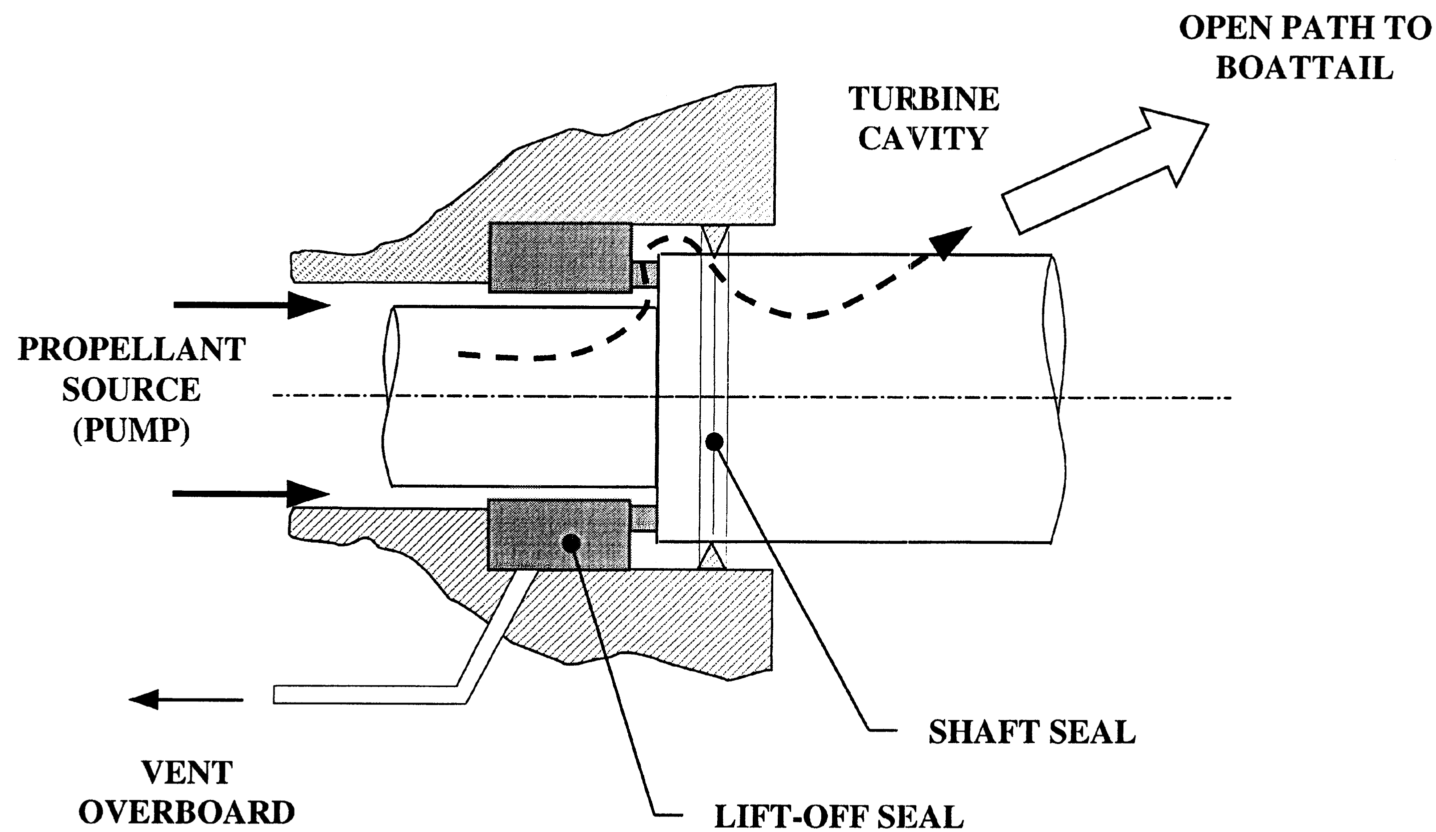
- Drains
  - Low sump pressure
  - Routing
    - Internal passages
    - External lines -- Engine or Vehicle mounted pump
  - Weight including support structure

- Buffer Gas Supply System (Helium)
  - Sources
    - Other users
    - Pressure control versus mass flow control

Inter-Propellant Seal System Design Considerations

- Shaft Seals
  - Materials
    - LOX Compatibility, Hydrogen Environment Embrittlement
    - Hard vacuum
  - Failure Mode Effects, Fail-Safe requirements
  - Thermal environment - large transient and steady-state gradients
  - Length -- significant effect on rotordynamics
  - Wear

Lift-off Seal System



Lift-off Seal System
Design Considerations

- Propellant Source
  - Supply Pressure and Temperature
    - Pressure must always be greater than turbine pressure
    - Usually cryogenic fluid

- Turbine Cavity
  - Pressure set by engine cycle and turbine flow direction

Lift-off Seal System
Design Considerations

- Lift-Off Seal
  - Closed under maximum pump inlet pressure during chill and shutdown
  - Open before minimum steady state operating point
  - Accommodate shaft axial travel
  - May require overboard vent line (low pressure sink)
- Shaft Seal
  - Leakage onto hot turbine components troublesome
  - Generally limited length available
  - Position upstream or downstream of lift-off seal influenced by turbine disc cooling requirements

Technology Development Needs

- Inter-Propellant Seals
    - Reduced leakage seals
    - Robust Seals - reduce buffer margin

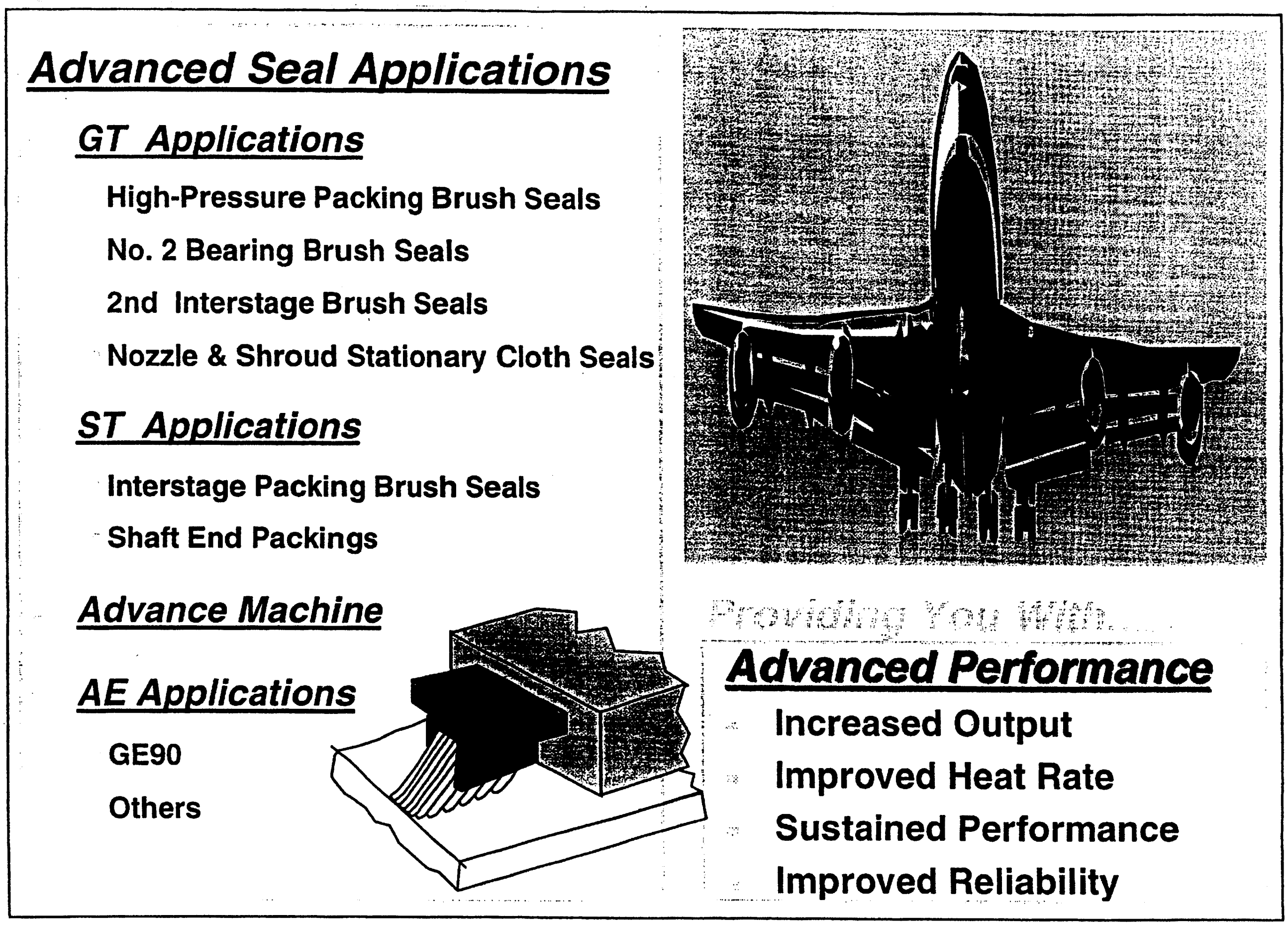
- Lift-Off Seal System
    - Combine lift-off seal with turbine shaft seal and eliminate overboard vent

ADVANCED SEALS FOR GE INDUSTRIAL GAS TURBINE APPLICATIONS

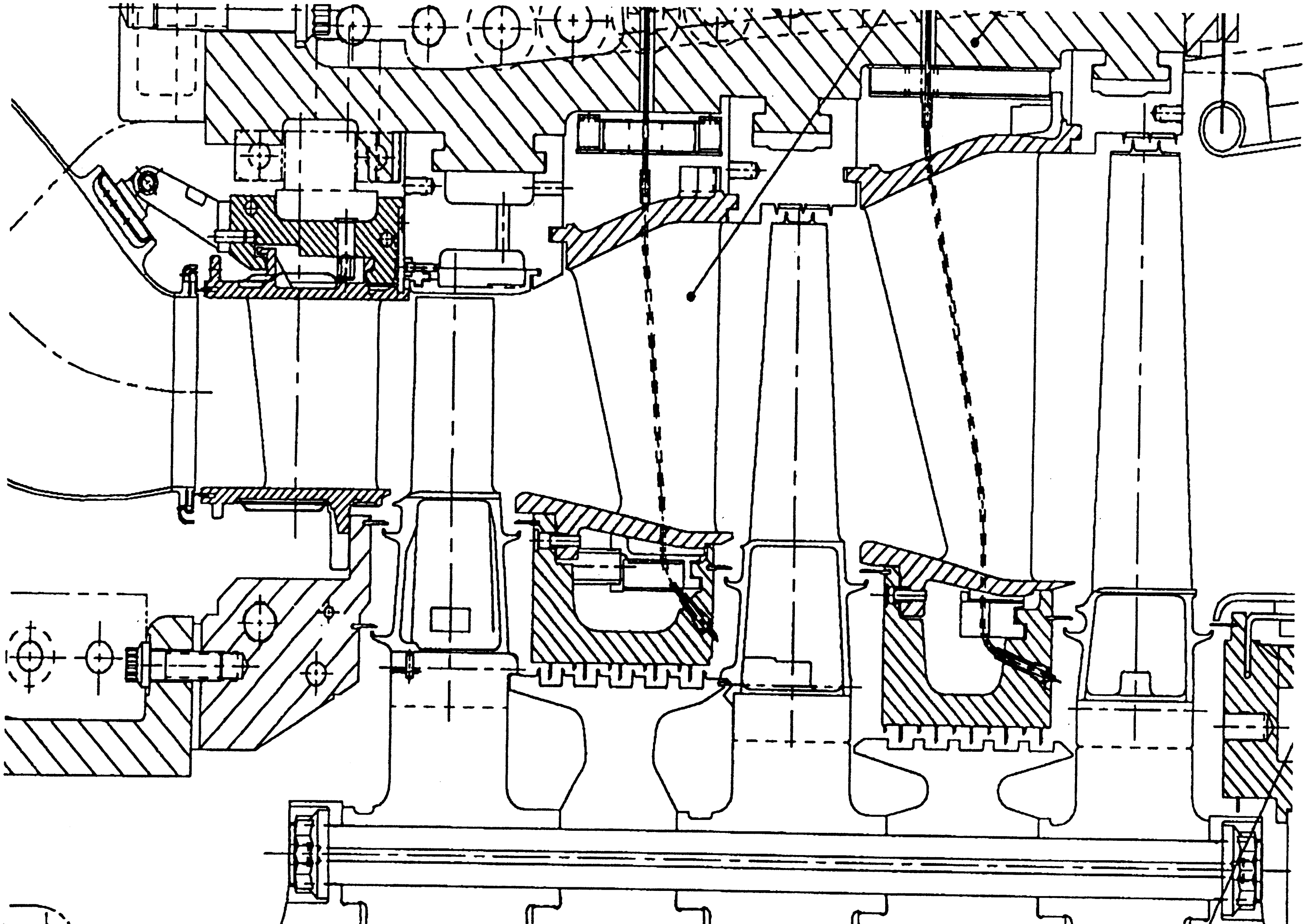
S. Dinc, G. Reluzco, N.A. Turnquist, and M. Zhou
General Electric Research and Development
Schenectady, New York

and

O. Kerber, F. Brunner, G. Crum, A.E. Stuck, R.H. Cromer
P.T. Marks, R.P. Chiu, and C.E. Wolfe
General Electric Power Generation
Schenectady, New York



7EA Gas Turbine Cross Section



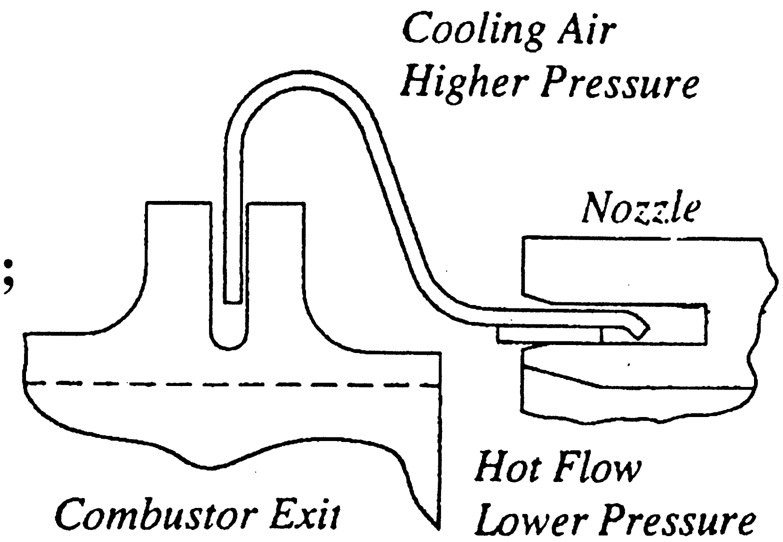
Frame Size	**Output (MW) (approx)**	**Brush Seal Location**	**Commercial-ization Date**
9E	123	HPP,#2 Bearing Seal	1996
7EA	85	HPP,#2 Bearing Seal	1996
6B	38	HPP	1996
52D	32	HPP,#2 Bearing Seal	1997
52C	28	HPP,#2 Bearing Seal	1997
51P	27	HPP	1997
32J	11	HPP	1997
32G	6	HPP	1997
7EA	**85**	**Interstage Diaphragm**	**1998**

Stationary Seal Applications:

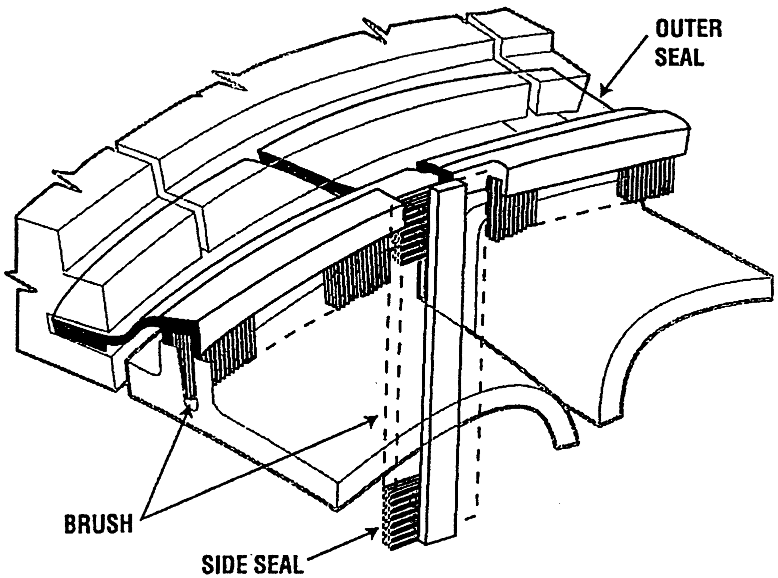
Different Sealing Arrangements

at Combustor Exit to Nozzle Junction;

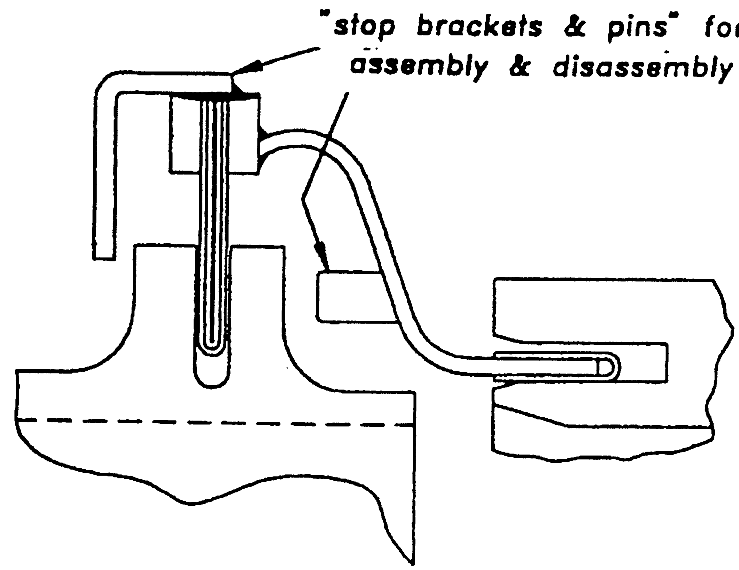
- **Current Seal Arrangement**
- **Stationary Brush Seals**
- **Stationary Cloth Seals**



(a) Previous sealing arrangement



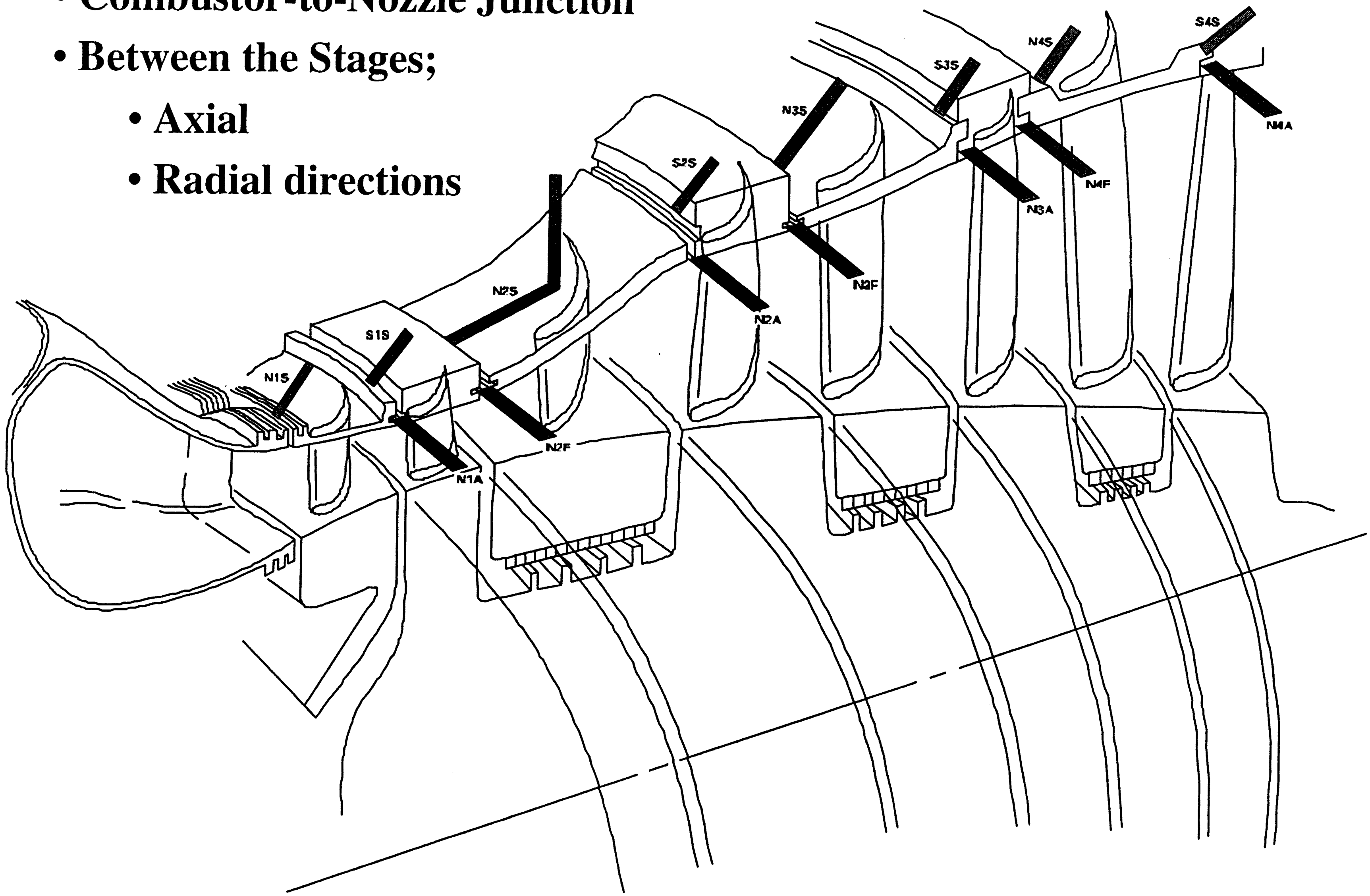
(b) Sealing arrangement with stationary brush seals



(c) Sealing arrangement with cloth seals

Cloth Seals at Turbine Hot Gas Path:

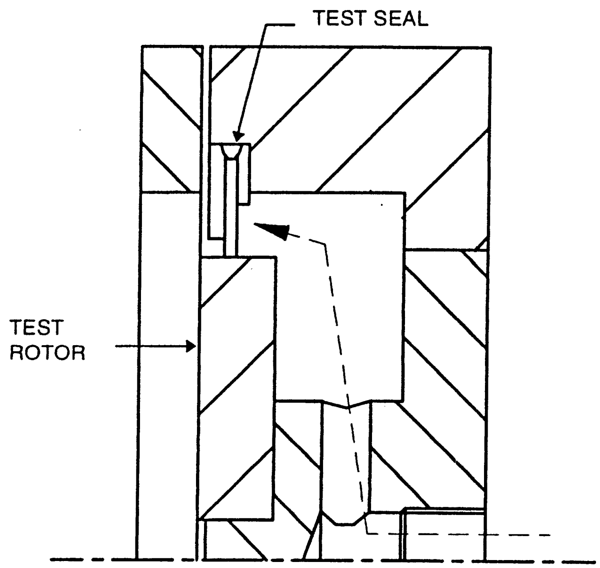
- Combustor-to-Nozzle Junction
- Between the Stages;
  - Axial
  - Radial directions



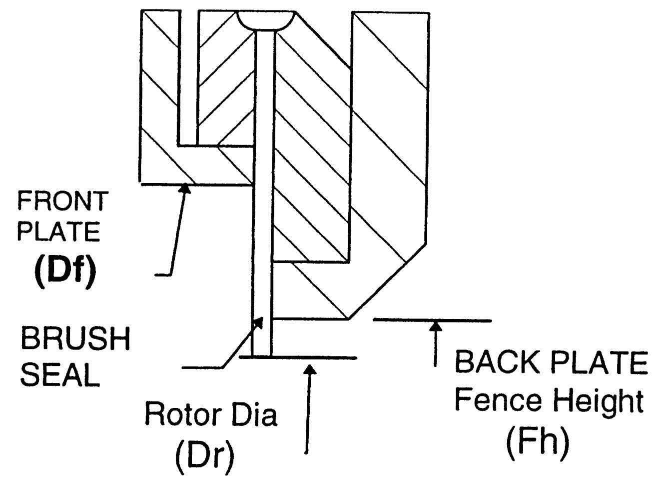
Rotational Seals: Brush Seal Development

Brush Seal Testing: Fundamentals

•Brush Seal Testing Configurations



Schematic of Static Test Rig



Test Seals with Interchangeable Front and Back Plates

Design Variables:

Seal	Wire Size inches	Bristle Density wires per inch
A	.0028	*A*
B	.004	*.73A*
C	.004	*1.47A*
D	.0056	*.53A*

Fh= 0.01, 0.05, 0.06, 0.073, 0.98, 0.123, 0.201

Dr= 5.10, 5.09, 5.80, 5.069

Seal Clearances= Line-to-line, 0.005", 0.01", 0.015"

R_f (D_f/2)= 0.796", 0.579", 0.451", 0.204"

Brush Seal Testing: Fundamentals

1. The characteristic curve of a brush seal is a function of the pressure drop across the seal

Fig.1. Effective Clearance for Seal B against Pressure Ratio (Fh=0.123")

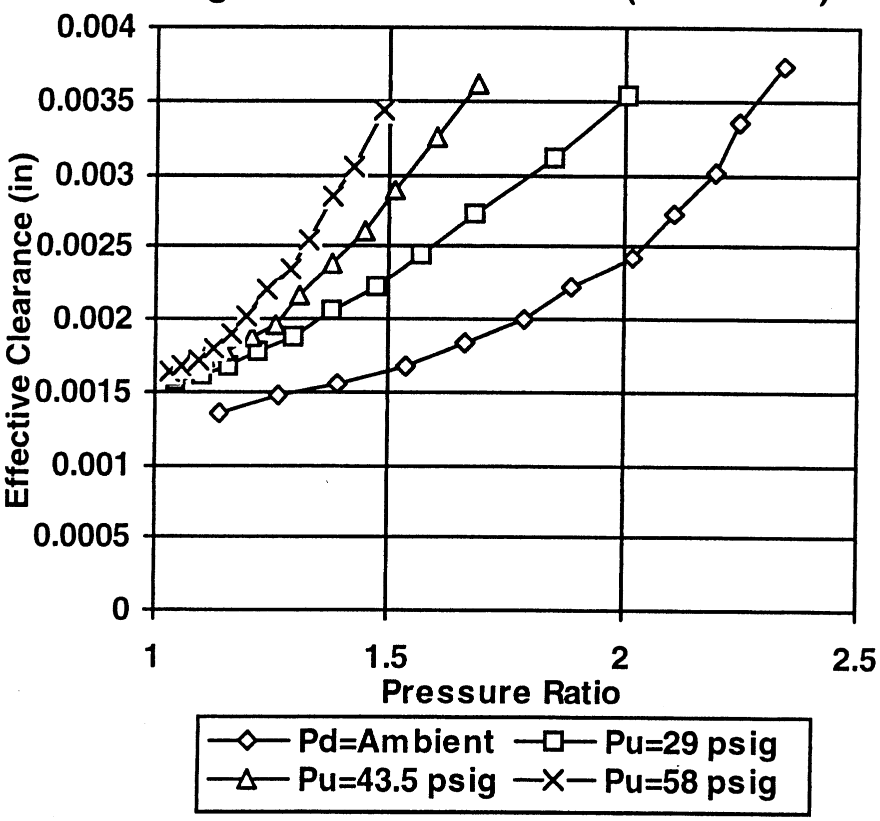
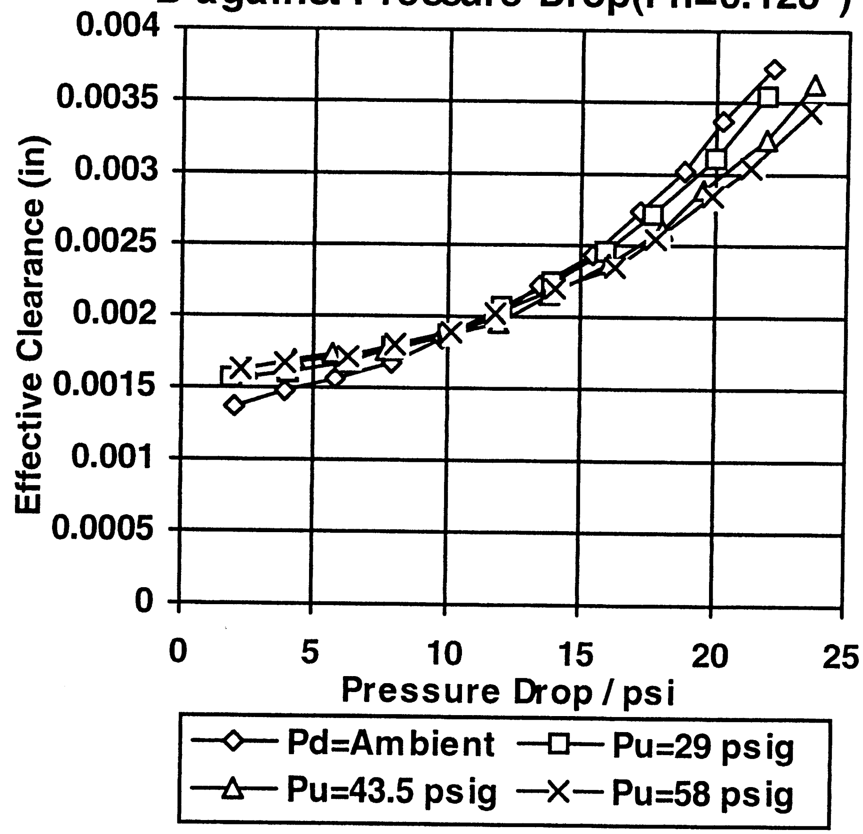


Fig. 2. Effective Clearance for Seal B against Pressure Drop(Fh=0.123")

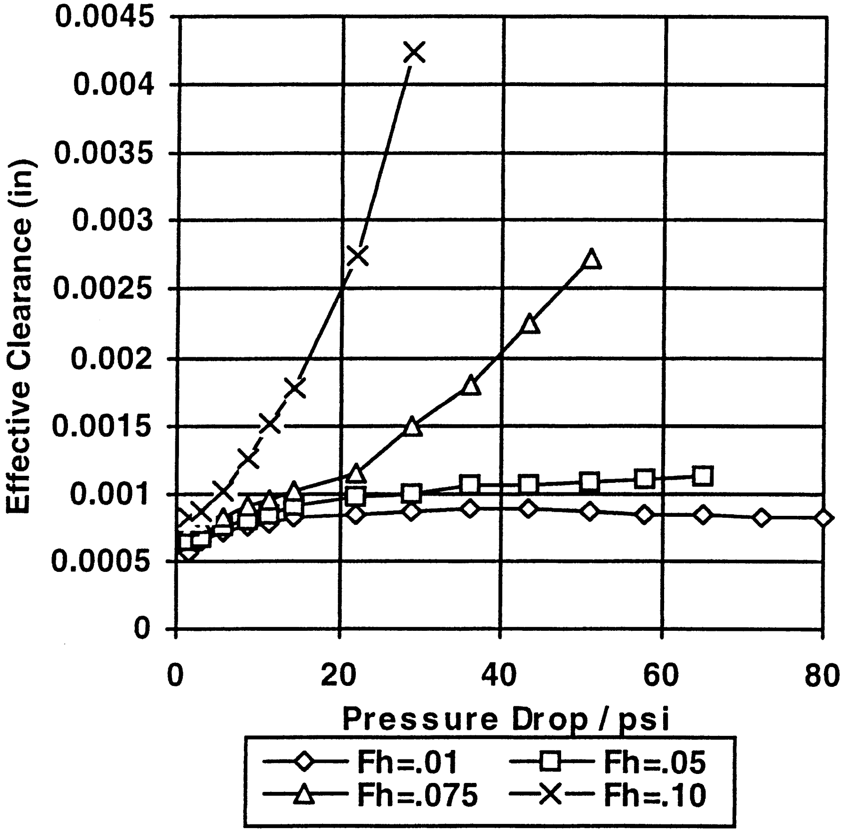


Every brush seal has a pressure drop capacity limit, on the seal B above this would be about 15 psi. This could represent a pressure ratio of 2 with ambient downstream conditions or only 1.15 with 100psia downstream, clearly two very different numbers.

Brush Seal Testing: Fundamentals

2. Typical Brush Seal Characteristic

Fig 3. Effective Clearance for Seal A against Pressure Drop

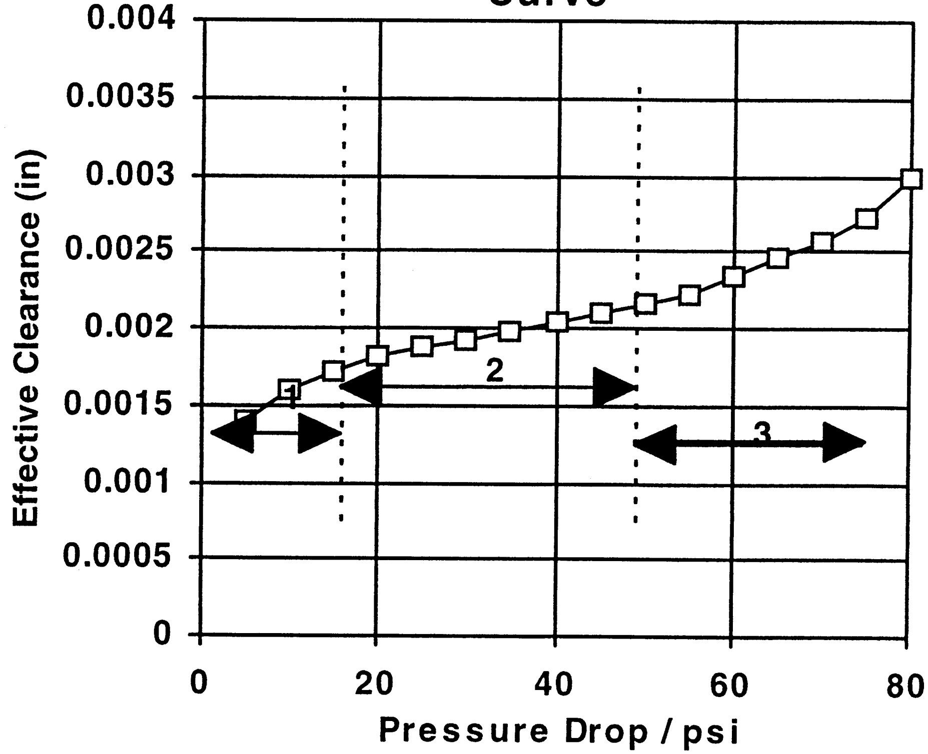


$$\text{clearance\_eff} = \frac{q\sqrt{(T1 + 460)}}{P1 . w . \mu}$$

μ the flow function is defined as follows:-

$$\mu = \sqrt{g.\gamma / R}.\sqrt{((2/(\gamma - 1)).PR^{-(\gamma+1)/\gamma}.(PR^{(\gamma-1)/\gamma} - 1))}$$

Fig. 4. Typical Characteristic Curve



A Typical Characteristics of a brush seal:

- Section 1 is usually from a pressure drop of 0 up to about 15 psi
- Section 2 is the area where most correctly designed seals function
- Section 3 is the area to be avoided when designing a brush seal

Brush Seal Testing: Fundamentals

3. Effect of Wire Size:

Fig 3. Effective Clearance for Seal A against Pressure Drop

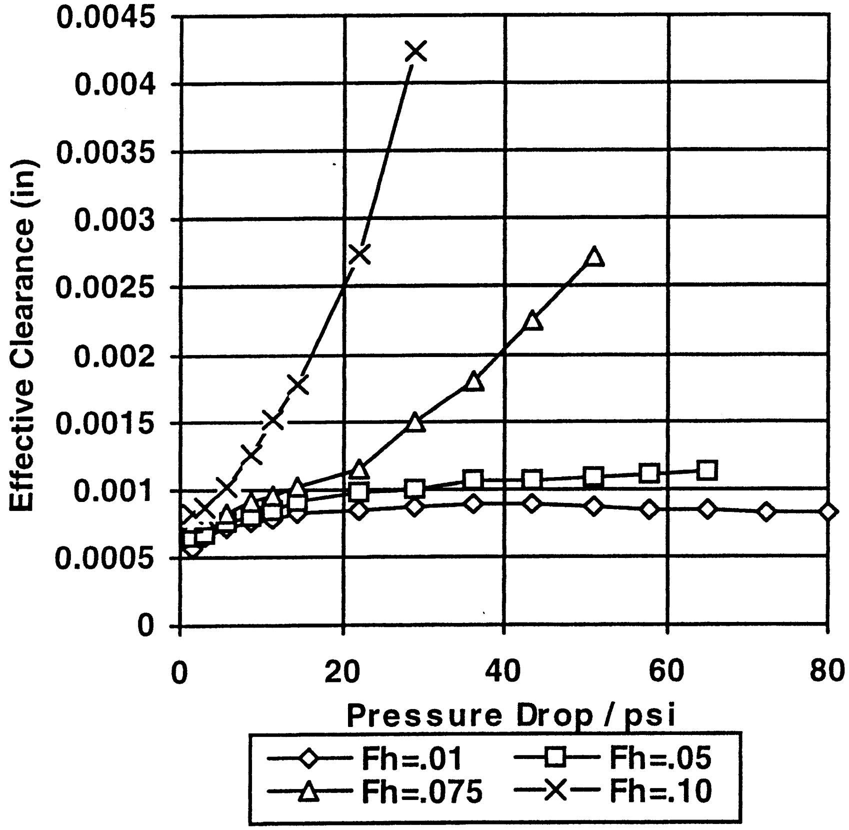
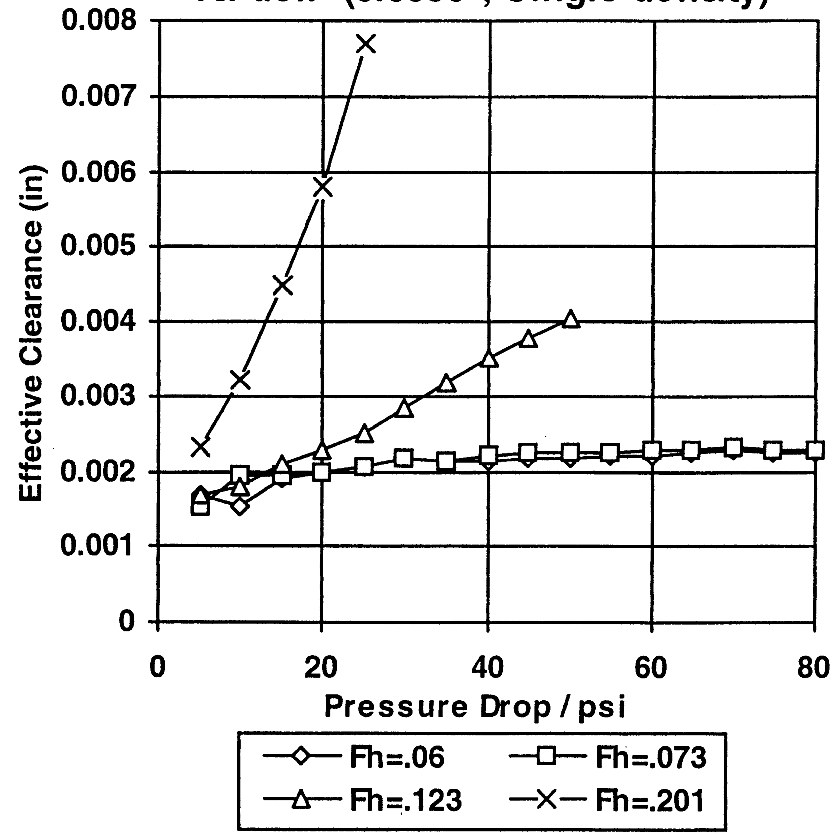


Fig7.Effective Clearance for Seal D vs. delP (0.0056", Single density)



Doubled Wire Thickness:

- Holds large pressure load
- Leaks more, Generates more heat and Higher wear rate

Brush Seal Testing: Fundamentals

4. Effect of Wire Density:

Fig 5. Effective Clearance for Seal B vs. delP (0.004", Single Density)

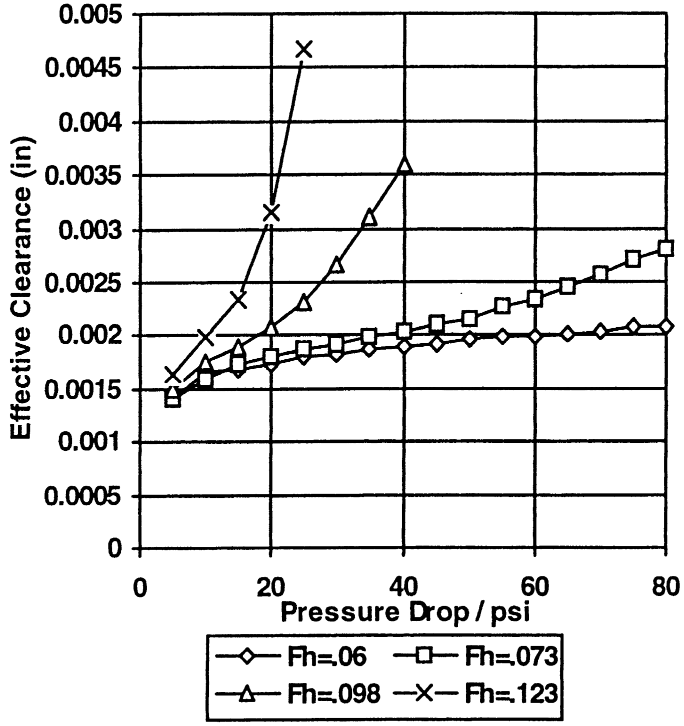
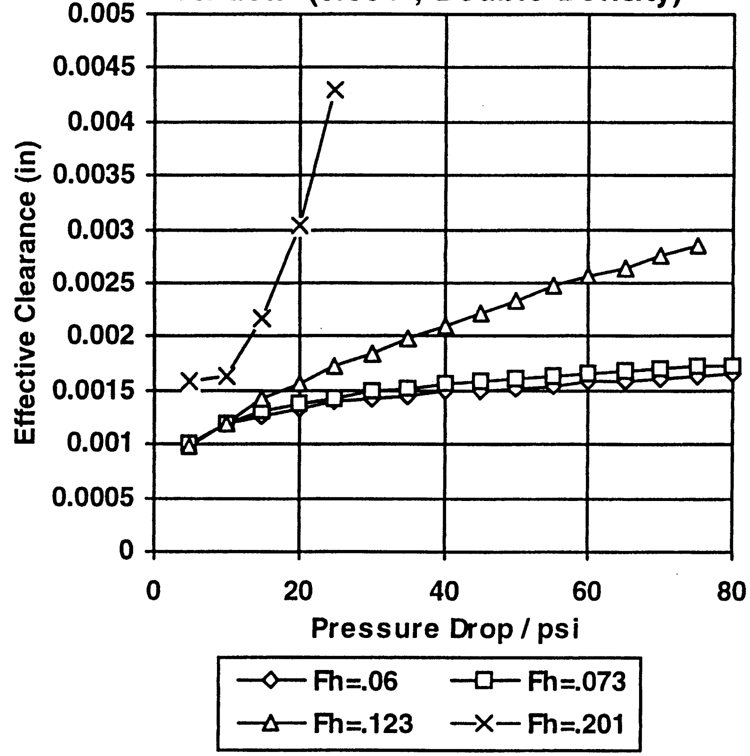


Fig 6. Effective Clearance for Seal C vs. delP (0.004", Double Density)

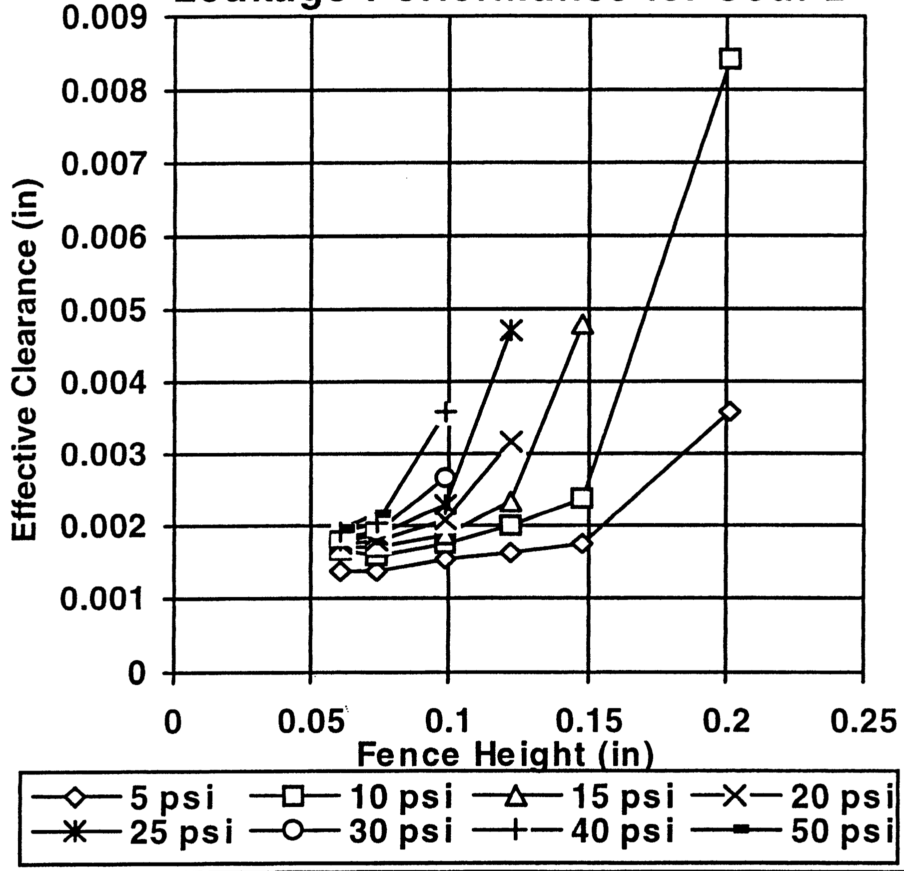


- **Doubling the wire density had the effect of reducing the leakage by some 30% whilst also more than doubling the pressure capacity.**
- **Larger wires exhibited higher pressure capacities but higher leakages.**

Brush Seal Testing: Fundamentals

5. Effect of Fence Height

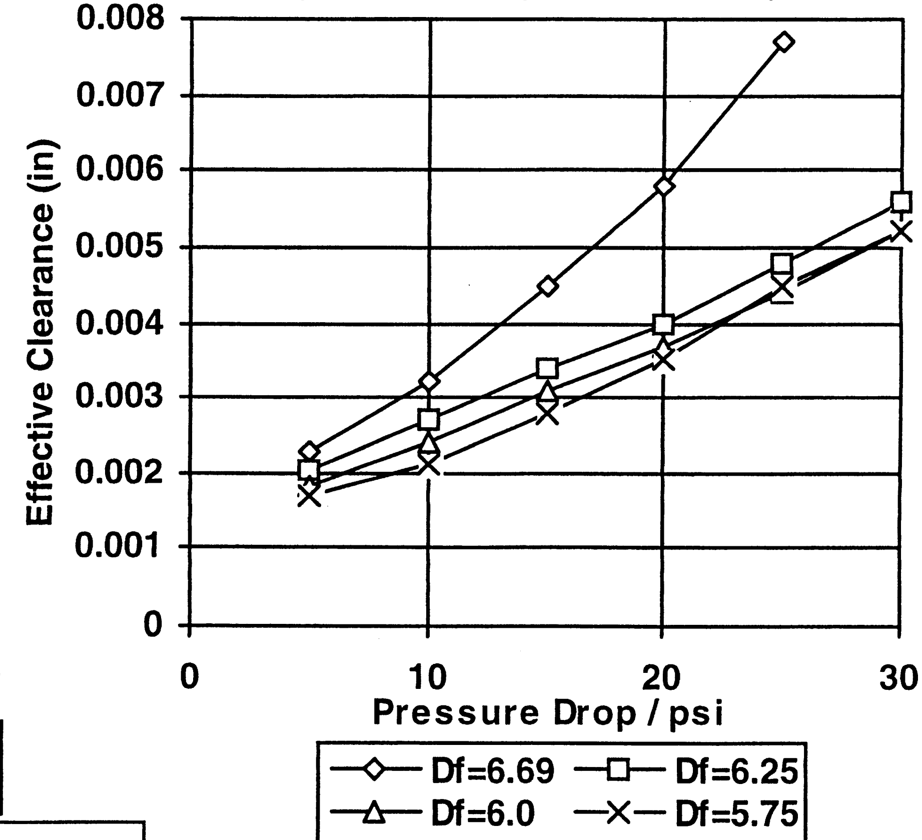
Fig 8. Effect of Fence Height on Leakage Performance for Seal B



The pressure capacity of any given seal can be increased and the leakage reduced by making the free bristle length shorter. This however can lead to other problems

6. Effect of Bristle Free Lenght

Fig 9. Effect of Front Plate Height on Leakage Performance for Seal D (Fence height, Fh=.201)

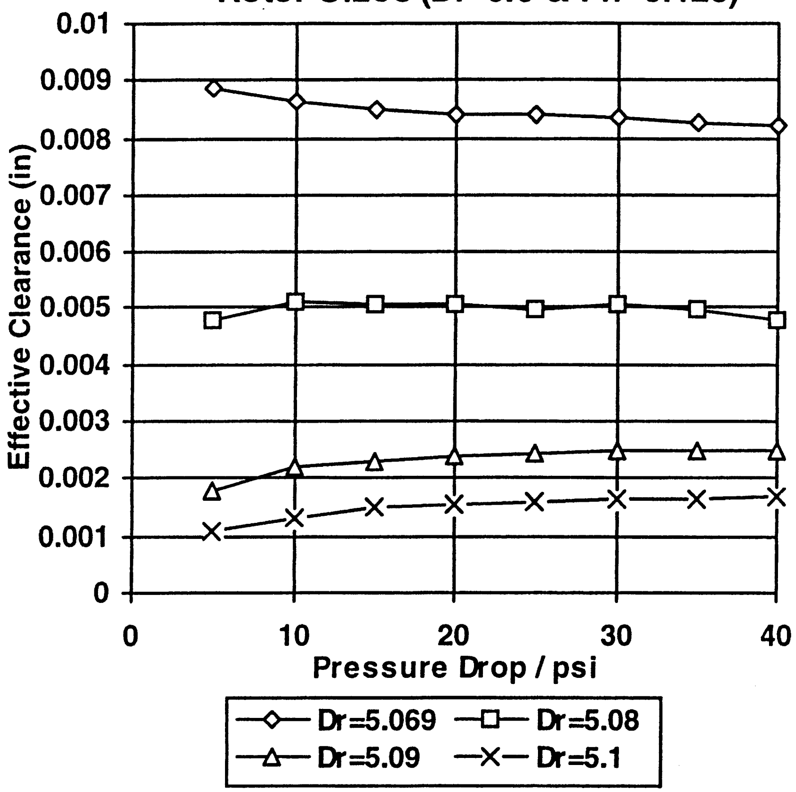


Decreasing the front plate bore and thus shortening the free bristle length has the effect of reducing the leakage.

Brush Seal Testing: Fundamentals

7. Effect of Clearance on Seal Performance

Fig 10. Effect of Clearance on Leakage Performance for Seal B with Varying Rotor Sizes (Df=6.0 & Fh=0.123)



Performance Evaluation:

- Rotor Dia Dr=5.10", Seal ID=5.093",
    - Seal Eff Clea: 0.0015 - 0.0017"
- Rotor Dia Dr=5.08", Seal ID=5.093"
    - <u>Seal Open Gap Clea: 0.0065",</u>
    - Seal Eff Clea: 0.005" (from 0.0015")
        - Increase Eff Clea: 0.0035"
    - <u>Seal Blow down: 0.003"</u>
    - Gap Discharge Coeff:
      Cd=0.0035/0.0065=0.54
- Rotor Dia Dr=5.069", Seal ID=5.093"
    - <u>Seal Open Gap Clea: 0.012",</u>
    - Seal Eff Clea: 0.0085" (from 0.0015")
        - Increase Eff Clea: 0.007"
    - <u>Seal Blow down: 0.005"</u>
    - Gap Discharge Coeff:
      Cd=0.007/0.0012=0.58

Brush Seal Design Process for Turbine Applications

I. Establish Seal Operating Conditions

- Phigh, Plow, delP, Temperature, RPM
- Excursions; Thermal transient Radial & Axial motion
- Startup/Shutdown cycles, Local vibrations,
- Flows; Required cooling flows, Fluid (air/steam),
- Geometric Considerations: Assembly stackup tolerances, Seal housing elipticity,
- Materials; Rotor material for wear, Seal housing material and expansion coefficient

II. Develop Prototype Seal - Identify and Retire Risks

1. Performance/Leakage/Hysterisis: Static and Rotational seal tests on test rigs at CRD, Cross, EGT, RPI and YFT Analysis

- Seal Design Parameters; # of Stages, Seal radial height, Bristle diameter, Seal fence height, Packing thickness, Assembly clearances, # of Segments
- Anti-hysterisis features,
- External cooling flow provisions,
- Seal long term performance

2. Wear: Sliding wear tests, Rotating wear tests

- Bristle material and diameter, Seal radial height,
- Bristle tip pressure, Seal stiffness,
- Seal life

3. Durability:

- Pressure tests w/ & w/o rotation; Seal geometry, fence height, Front & back plate geometry, # of seal stages, Bristle pack spacing, Seal axial location
- Bristle material evaluation for higher temperatures and rotor materials
- Bristle flutter, Primary seal flow impingement; CFD Analysis, FE Analysis

4. Turbine Cooling Flow YFT Analysis:

- Turbine section cooling requirements, current cooling circuit, flows w/Brush Seal,
- Performance improvements predictions

5. Effect on Rotor/Rotordynamics:

- Temp rise test, FE Analysis, Bristle tip pressure, Frictional rotor heating,
- Rotor dynamic stability analysis

6. Producibility/Assembly:

- Seal cross-sectional design, # of segments, End gap configuration,
- Assembly trials, Anti-rotation devices, Seal & housing materials
- Instrumentation

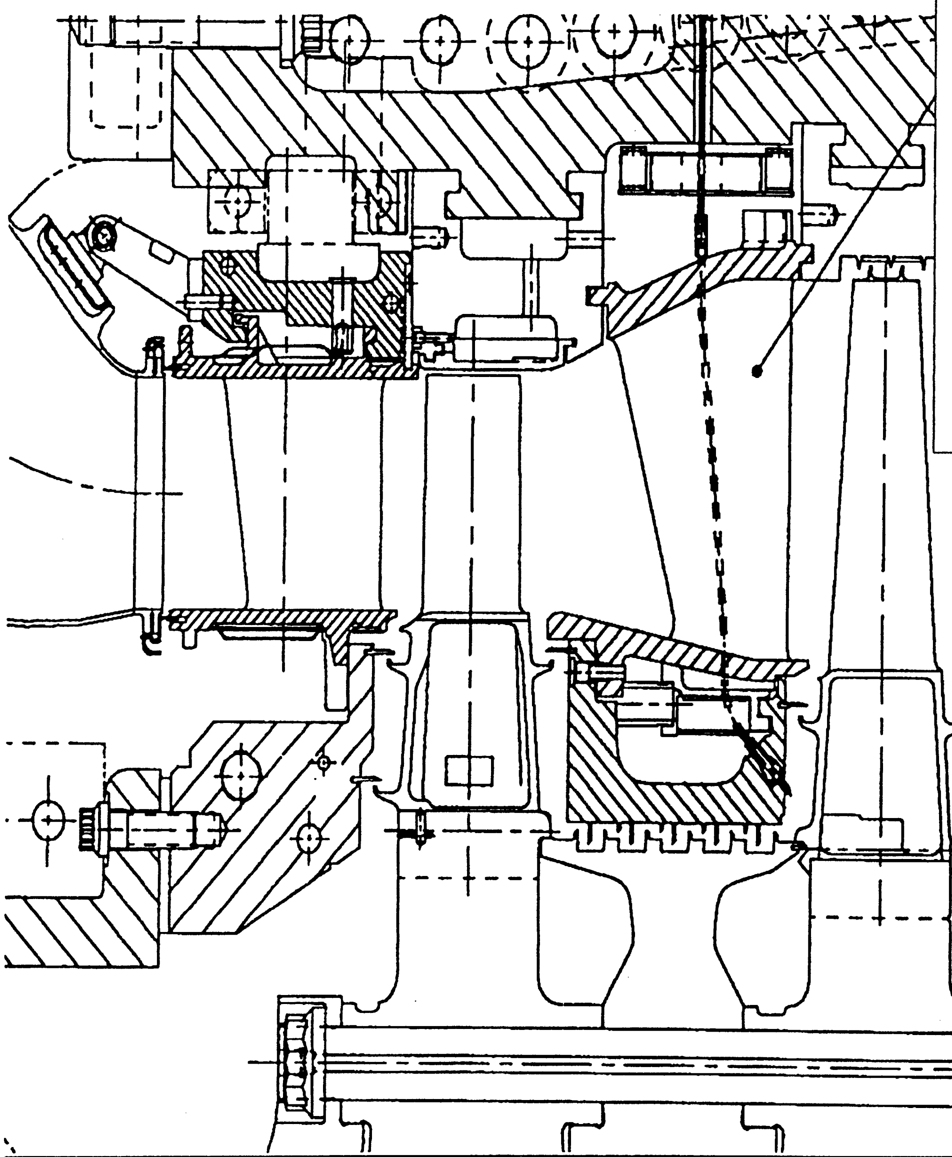
III. Establish Final Brush Seal Design:

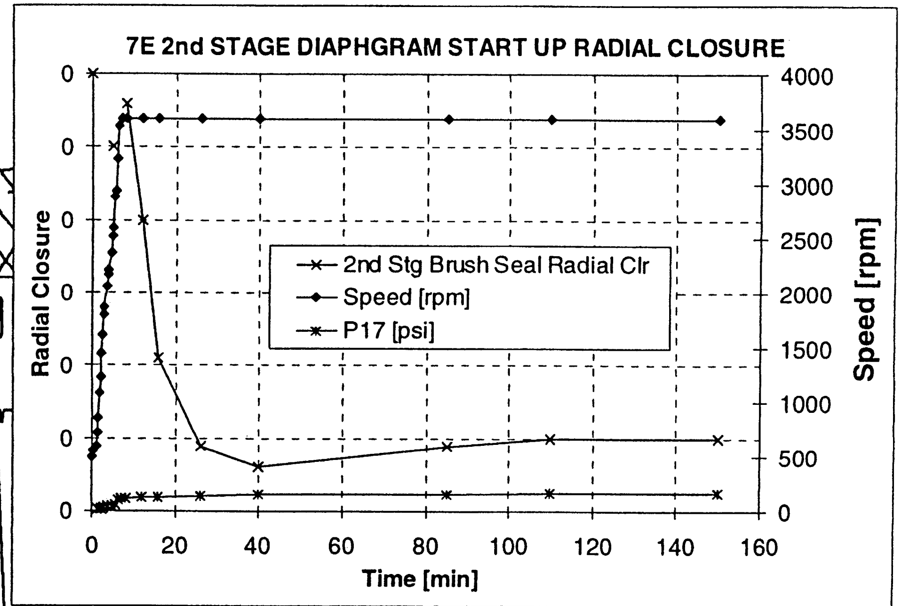
- Proof Test on a full scale production turbine
- Field Prototype Installations; Seal Installation, Field Instrumentation
- Field Testing; Performance testing, Seal performance degradation monitoring

Each Brush Seal Product Implementation Has Own Unique Features Requiring Specific Seal Design and System Considerations

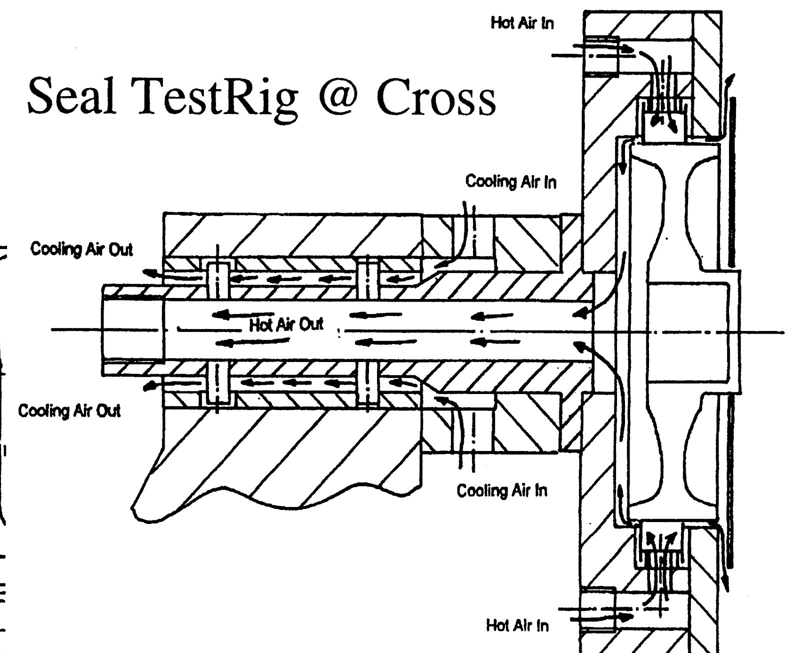
Brush Seal Application:

- Interstage Sealing

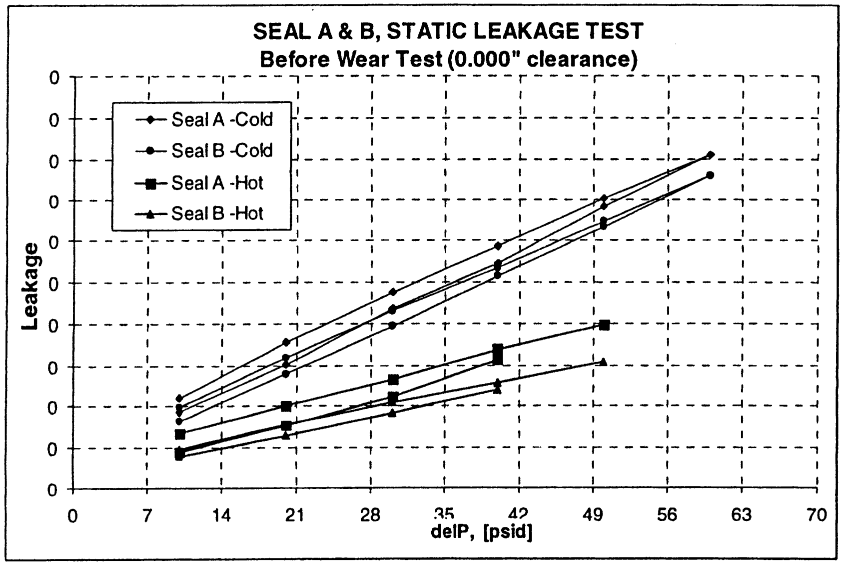


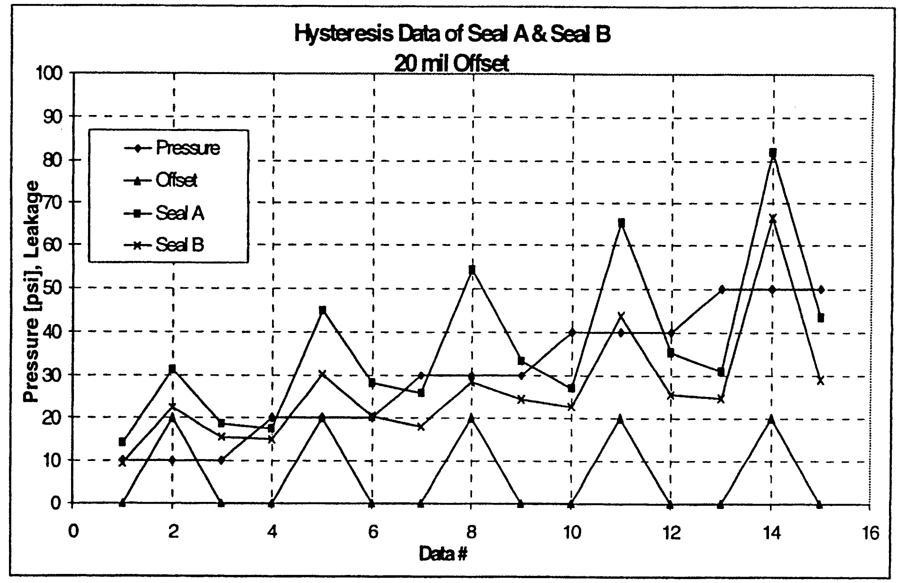


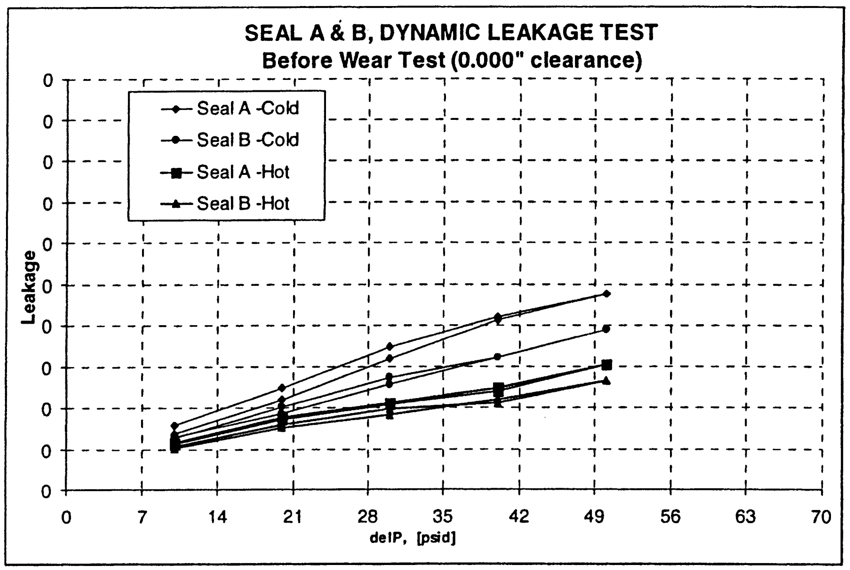
Seal TestRig @ Cross

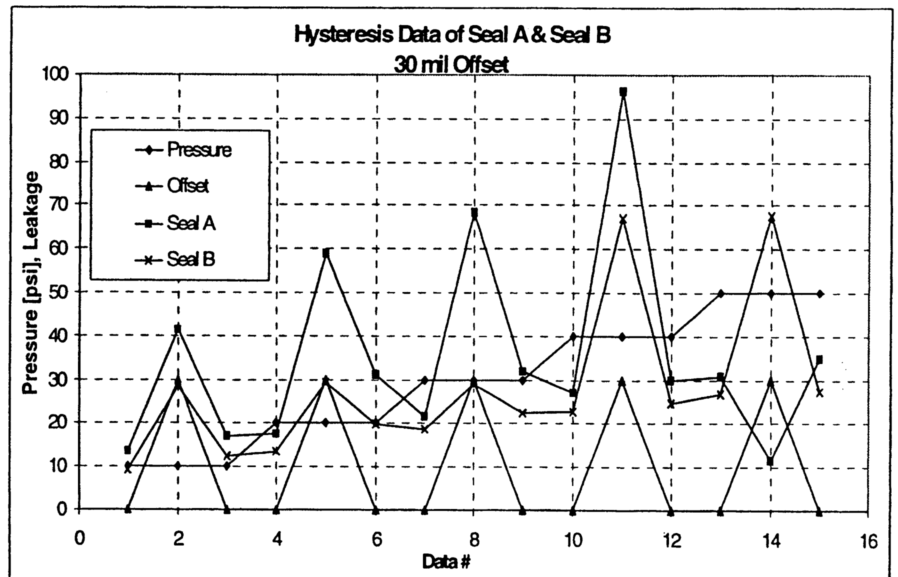


Intersatge Seals: Leakage and Hysterisis

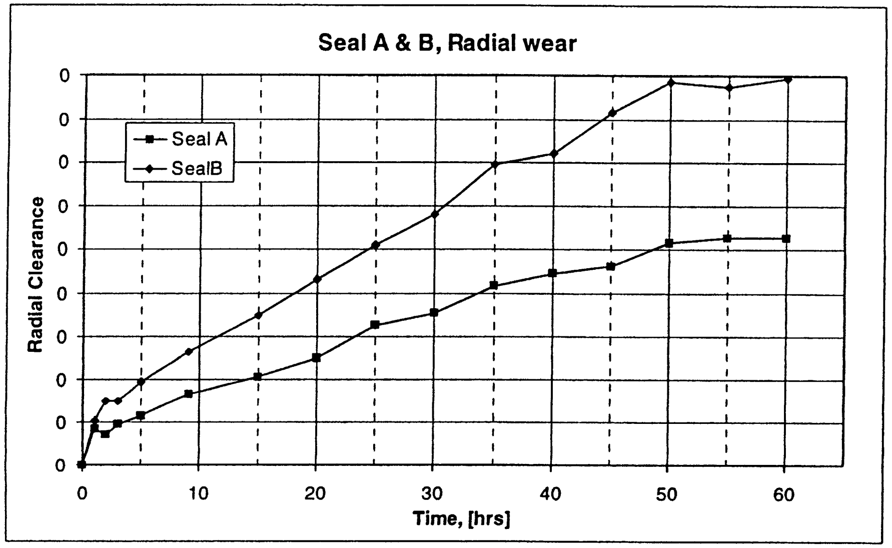


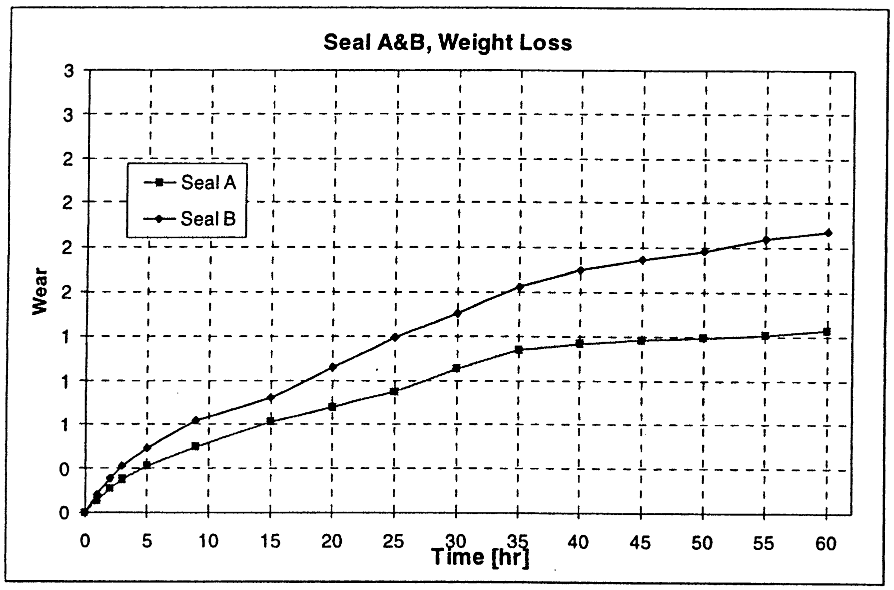


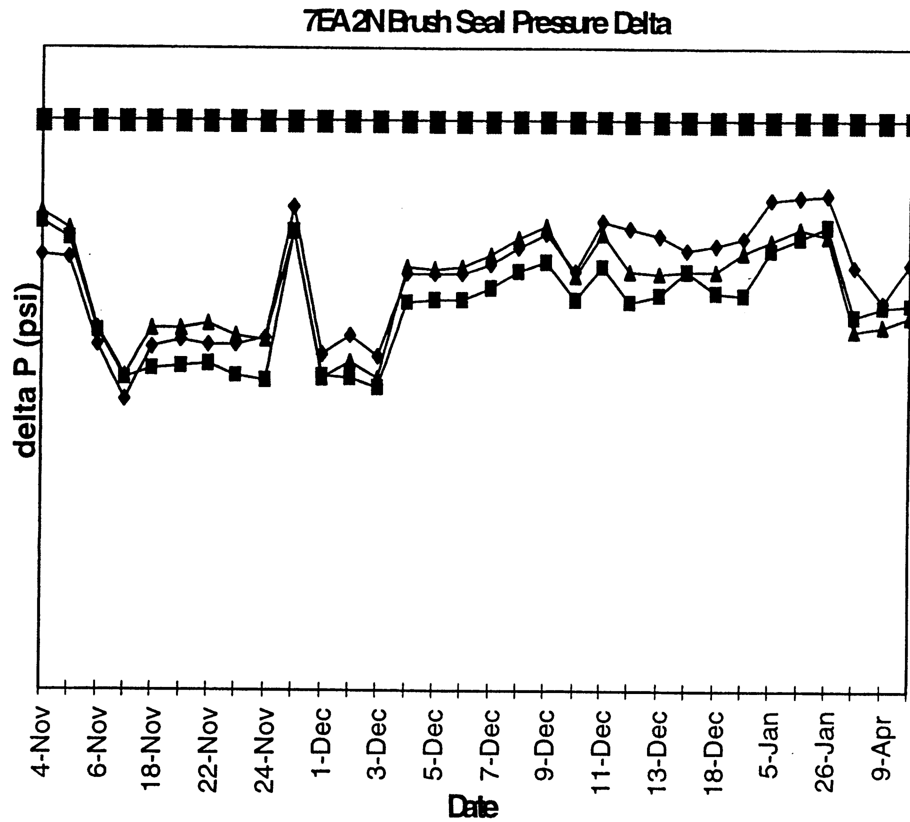




Intersatge Seals: Wear Test and Field Pressure Data

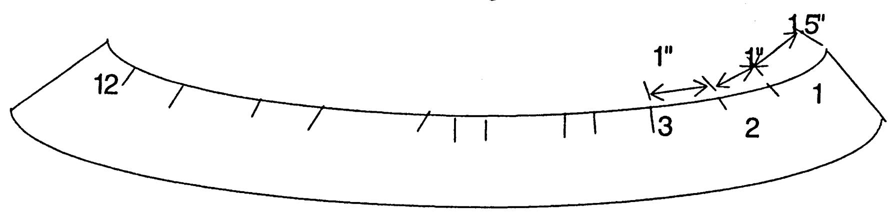






Brush Seal Stiffness Measurements

Test Locations along Brush Seal



Note: Location 1 is about 1.5" in from the "loose bristle" end; each point thereafter is 1" from the previous point (some seals had more locations than others).
The compressor was aligned so that its centerline was directly above each measurement point, perpendicular to the tangent on the arc at that point.

Location #	Seal from Vendor #1 (psi/mil) *Design Kbr=0.25 psi/mil*	Seal from Vendor #2 Stiffness (psi/mil) *Design Kbr=1.0 psi/mil*
1	0.42	2.87
2	0.65	6.18
3	0.67	5.38
4	0.89	5.77
5	0.48	3.64
6	0.56	2.42
7	0.52	7.00
8	0.65	4.50
9	0.71	5.13
10	0.60	5.21
11	0.34	4.96
Average	**0.59**	**4.82**

Advanced Seal Test Rigs at CRD

	"Shoebox" Rig	5.1" Rotary Rig	36"/50" Rotary Rig
Working Fluid	Air	Air or Steam	Air
Total Flow Rate (lbm/s)	2.0	1.5 Steam/2.0 Air	12
Inlet Pressure (psig)	430	1200 Steam/450 Air	125
Exhaust Pressure (psig)	430	300	125
Temperature (°F)	1000*	750 Steam/1000 Air*	100
Speed (RPM)	N/A	36000	2400
Surface Speed (ft/s)	N/A	800	375
Axial Motion (in.)	N/A	+/- 0.75	N/A
Seal Configuration	12" max. linear strip (1 seal strip)	5.1" diameter brush, labyrinth, etc. (2 seals req'd)	36" dia. brush, aspirating, etc. (2 seals req'd)

<u>Note</u>: Temperature limits depend on test pressures. Limits given are ablsolute maximum.

5.1" Test Rig Capabilities

<u>Leakage testing</u>

Single stage brush seals tested up to 400 psid in air; up to 1200 psid possible in steam.

<u>Wear testing</u>

Long term seal and rotor wear testing under same conditions as leakage testing.

<u>Seal hysteresis testing</u>

360° Seal/Rotor interference can be applied/removed by moving entire rig housing relative to stepped rotor, with applied pressure.

<u>Rotor heating evaluation</u>

Rotor surface temperature measured using infrared fiber optic probe adjacent to brush seal; thermal imaging camera used to evaluate zero-pressure frictional heat generation.

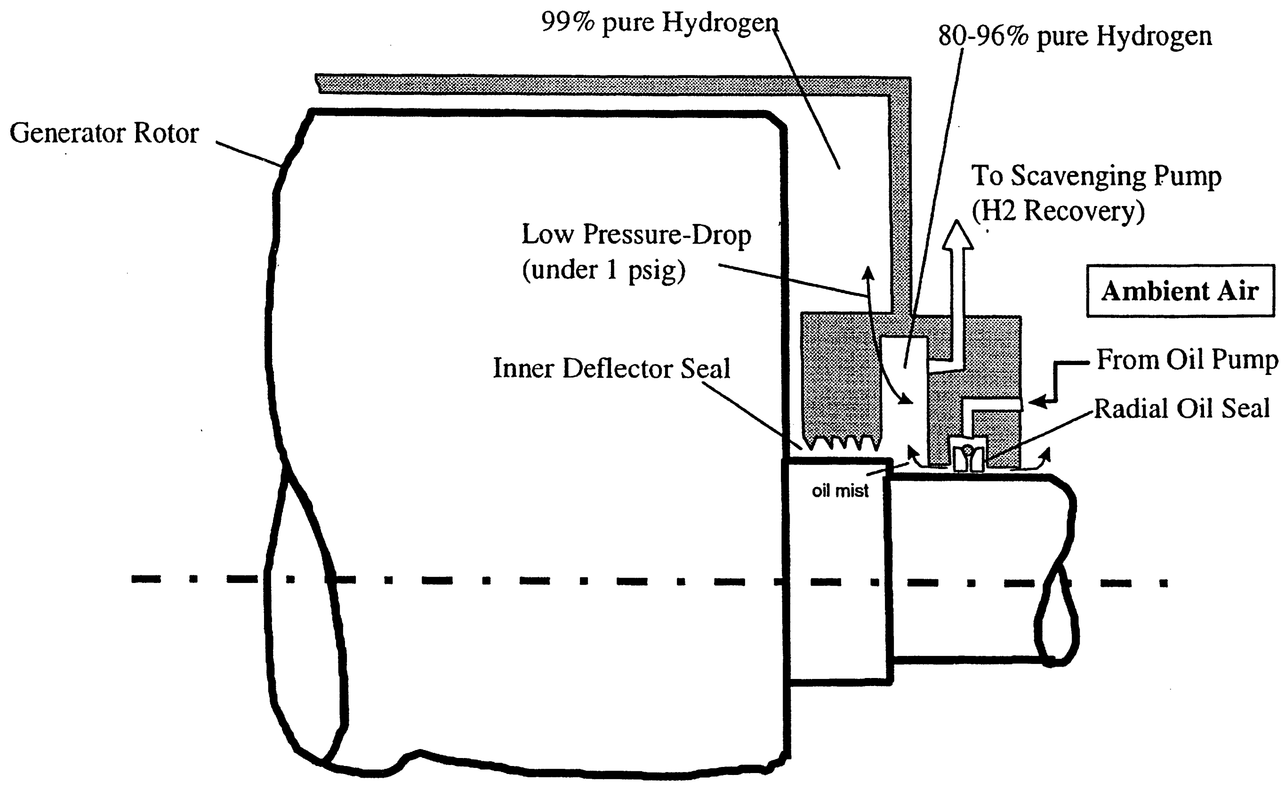
<u>Rotordynamic evaluation</u>

Two Bentley-Nevada proximity probes per bearing for full rotor vibration evaluation (Rotor orbits, Vibration vs. Speed, Vibration vs. Time, Vibration Spectrum Analysis).

CHALLENGES IN HYDROGEN SEALING FOR GENERATORS

Bharat Bagepalli, Mahmut Aksit, and Rob Mayer
General Electric Company
Schenectady, New York

Hydrogen Sealing System for a Generator



Why Hydrogen ?

- Hydrogen has seven times the heat-extraction capacity of air.
- Use of hydrogen for cooling large turbo-generators substantially reduces their size - compared with using air.

Major Issues and Challenges

- At 30-75% concentration, hydrogen in air is explosive.
- Secondary sealing system needs to perform in an oil-mist + hydrogen environment.
- Sealing must occur under low pressure-drop and diffustion conditions.
- Generators need to be contiually replenised with hydrogen to compensate for consumption.
- Hydrogen may not be easily available in remote areas, and with overseas customers - some are forced to build an auxiliary H2 plant nearby for this.
- Handling hydrogen is not as simple as air.

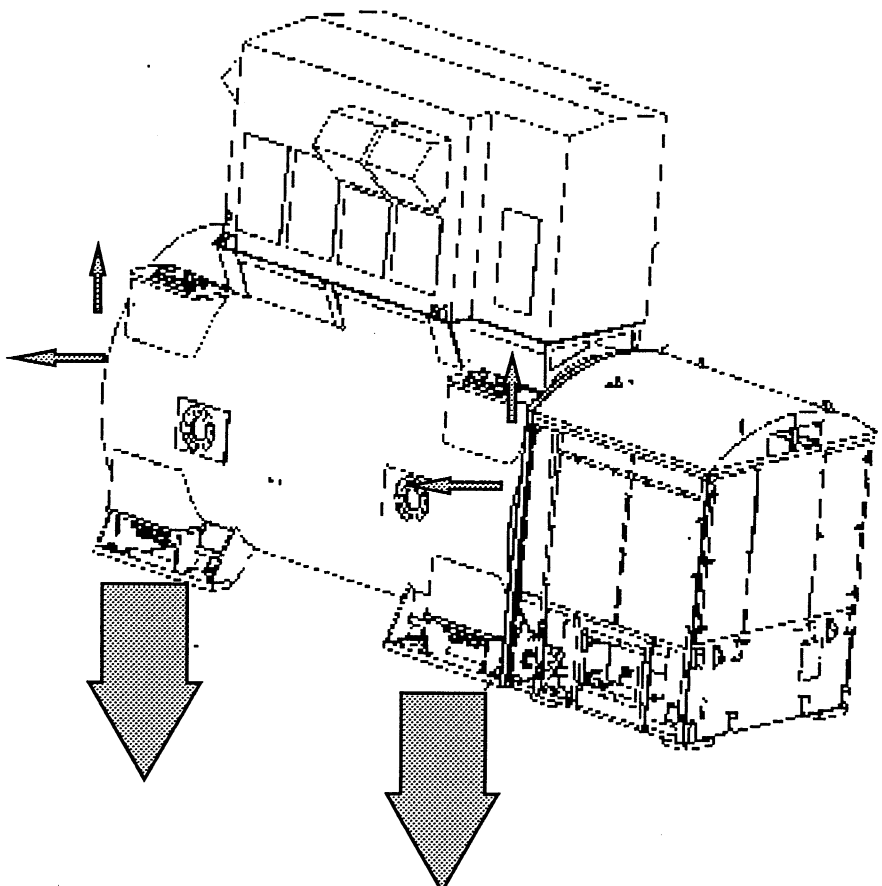
Objectives

- Reduce H2 consumption by 50%.
- Oil-seal management: reducing H2 consumption requires simultaneous reduction of oil flow to maintain H2 concentration in Scavenging Chamber above explosive levels.

Approach

- Use Brush Seals.
- Reduce oil flow requirement: use a smaller pump.

Identifying Sources of Hydrogen Consumption

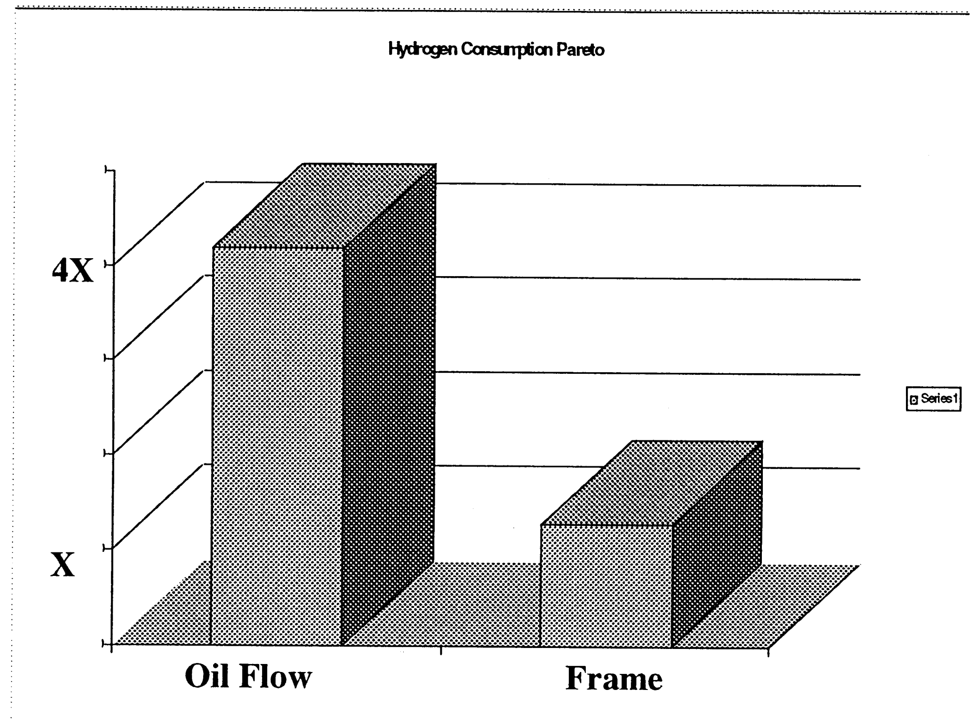


30" DIA
Journal

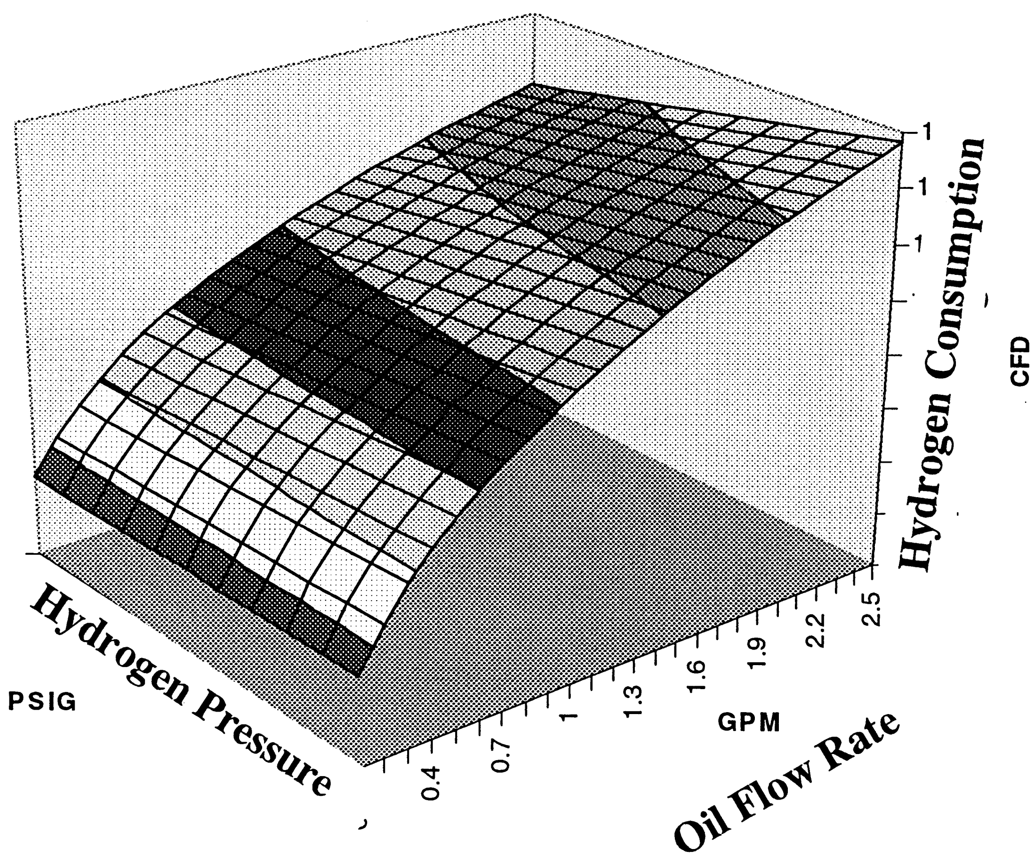
Major Components:

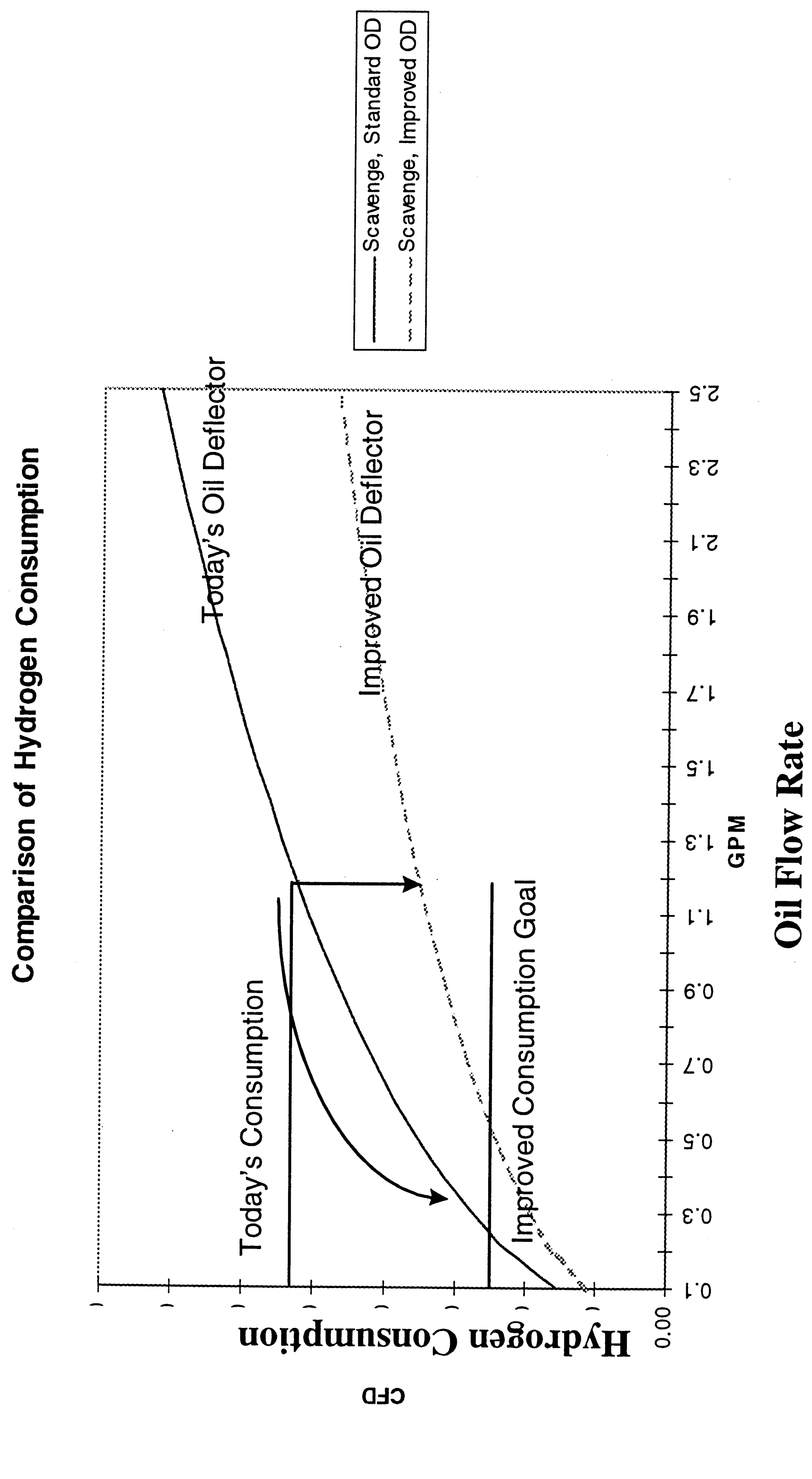
Oil Flow
(hydrogen dissolved in sealing oil)

Frame Leakage
(tiny weld inperfections, imperfect joint sealing)



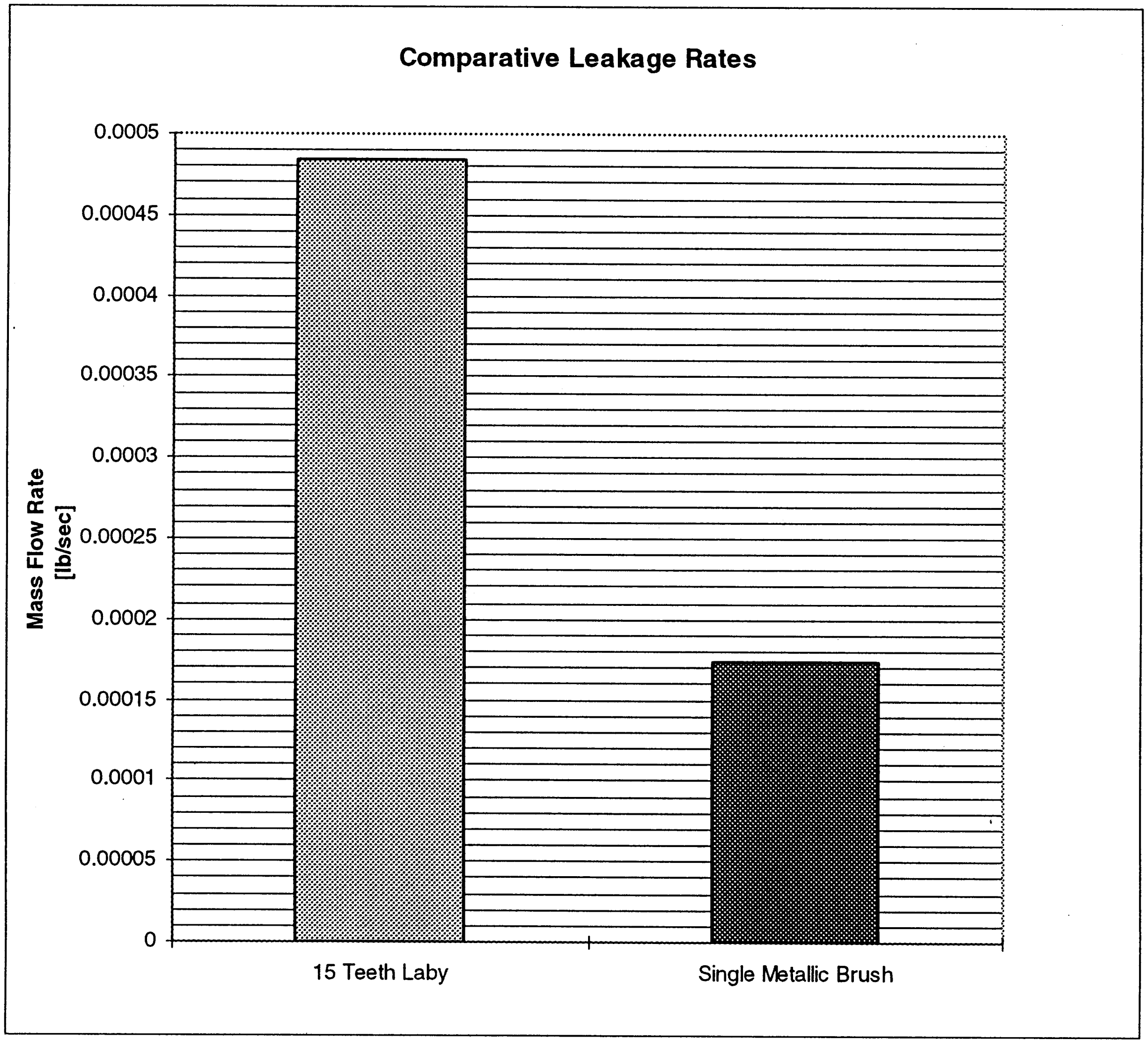
Scavenging Hydrogen Consumption with varying Pressure





Comparison of Hydrogen Consumption
Today's Oil Deflector
Improved Oil Deflector
Today's Consumption
Improved Consumption Goal
Scavenge, Standard OD
Scavenge, Improved OD
0.1
0.3
0.5
0.7
0.9
1.1
1.3
1.5
1.7
1.9
2.1
2.3
2.5
GPM
Oil Flow Rate
0.00
Hydrogen Consumption
CFD

Preliminary results: 15-Tooth Laby vs. Brush



ADVANCED SEAL DEVELOPMENT FOR SIEMENS WESTINGHOUSE
COMBUSTION TURBINES

Raymond E. Chupp
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Orlando, FL 32826-2399

Advanced Sealing Development for Siemens Westinghouse Combustion Turbines

Raymond E. Chupp , Fellow Engineer
Siemens Westinghouse Power Corporation, Orlando, Florida

Presented at the 1998 NASA Seal/Secondary Air Delivery Workshop
NASA Lewis Research Center, Cleveland, OH, October 22, 1998

Development is done in part under the Advanced Turbine Systems (ATS) cooperative program cooperative with the U.S. Department of Energy. The ATS program is administered by the Federal Energy Technology Center, FETC--Program Manager: Dr. Richard A. Johnson

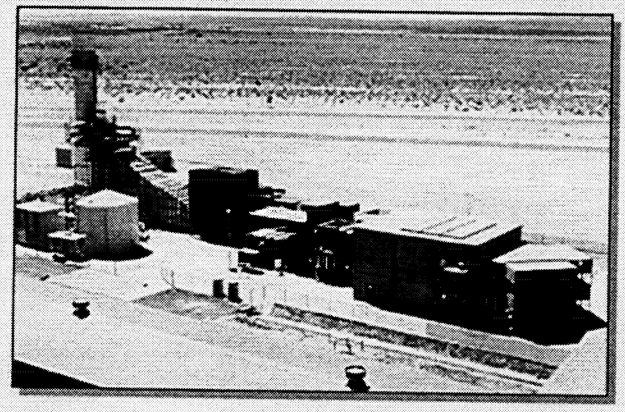
Siemens Westinghouse Power Corporation was formed from Siemens AG of Germany and Westinghouse Power Corporation in August of this year (1998).

ABSTRACT

Several efforts are in progress at Siemens Westinghouse to develop advanced sealing for large utility industrial gas turbine engines (combustion turbines). Much of this effort focuses on transitioning aero gas turbine technology to combustion turbines. Brush seals, film riding face and circumferential seals, and other dynamic and static sealing devices are replacing labyrinth and other seals. For combustion gas turbines, advanced sealing can significantly reduce leakage flows because of the enormous size of the components and the relatively constant operating conditions. Challenges include: extremely long operating lives; infrequent but large position excursions; difficulty in coating or treating larger components; plus maintenance, installation, and durability requirements. The development includes rig testing and engine validation of prototype designs. This effort is part of the Advance Turbine Systems (ATS) engine development being done under a cooperative agreement between Siemens Westinghouse and the US Department of Energy, Office of Fossil Energy.

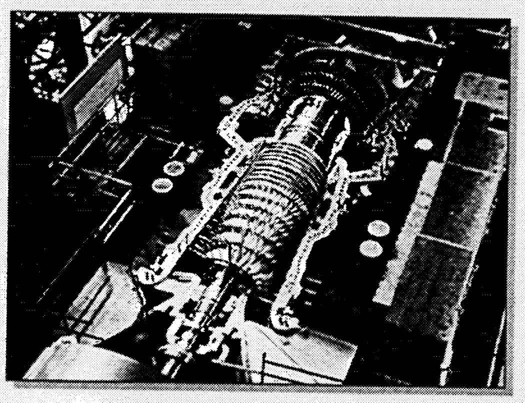
What is ATS? -- The Next Generation of Gas Turbine Technology

- Key to America's competitiveness in the global electrical market
- A university, utility, industry, government partnership. Supported by universities and vendors throughout US
- Lowest cost producer of electricity (10+% reduced electricity cost ==> >60% net plant eff.)
- Environmentally superior (< 10 ppm NOx emissions)
- Fuel-flexible design--natural gas + future use of coal or biomass fuels
- Reliability-availability-maintainability (RAM) maintained
- Commericialization near Y2K

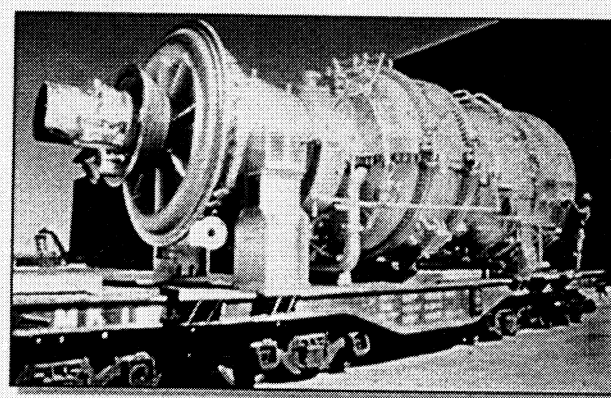


The Department of Energy's (DoE's) ATS program is a major driving force in the U.S. to improve industrial power plants. Over the last few years, large combustion turbines have evolved via. integrating advanced technology into their design. Overall plant efficiencies have increased from under 40% to over 60% in the ATS plant being developed. ATS objectives address efficiency, emissions, cost of electricity, fuels, RAM, and commercialization by near Y2K. The ATS program is a catalyst for the power generation industry to develop the next generation of gas turbine technology.

Large Combustion Turbines



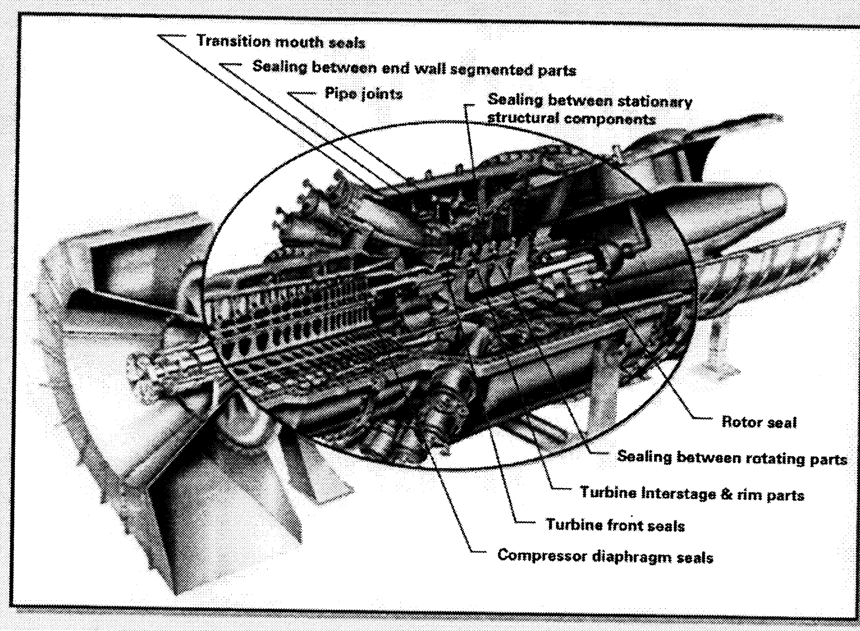
During assembly



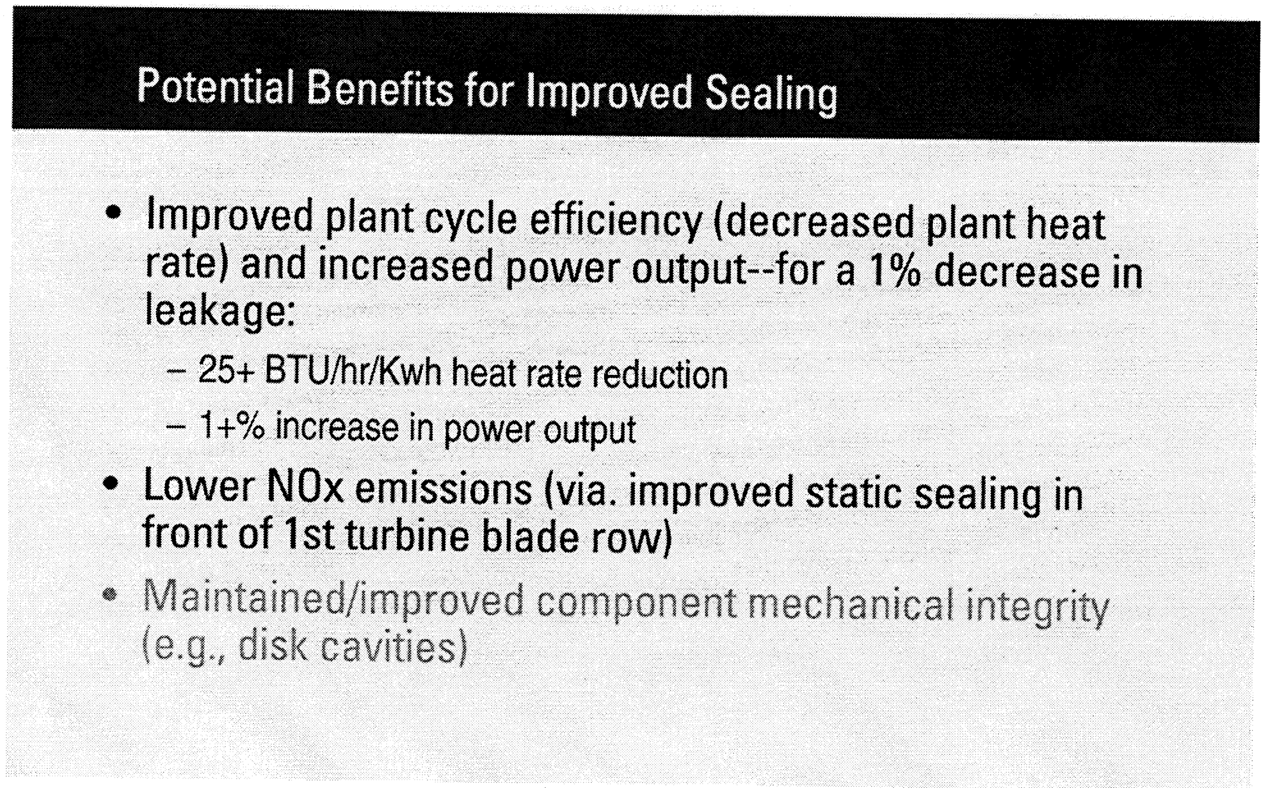
Prepared for shipment

The man in the background on the right gives an indication of the size of the large gas turbines used in the utility industry. The turbines have a split casing as shown on the left. This offers convenience in assembly and in the field repairs. However, when the rotor is removed the lower half of seals are at risk of someone walking on them. So the seals need to be designed to withstand this event.

501ATS Advanced Sealing Technology

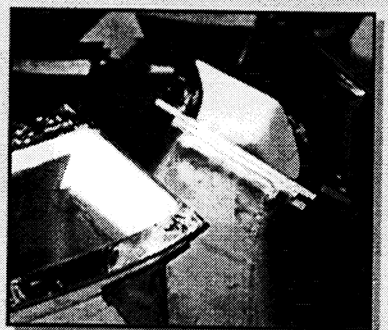


The various types of advanced sealing applications addressed in the 501ATS are shown by the callouts on this chart; static types are denoted at the top and dynamic ones on the bottom. In the 501ATS, the closed-loop rotor cooling air is brought in from the rear and exits from the front of the turbine into the compressor exit cavity. Today, the main areas of this presentation are transition mouth seals, brush seals, and the rotor rear seal.



The benefits of the improved sealing in improved performance and lower emissions are significant in comparison to the cost of the new hardware.

Transition Mouth Sealing



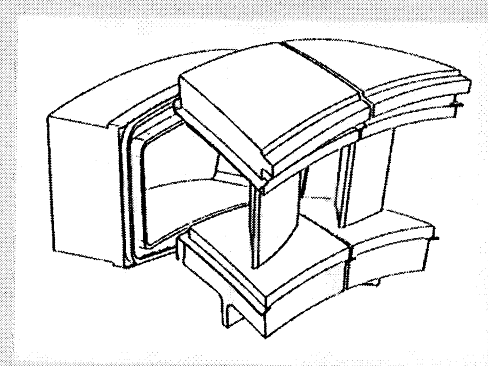
Transition mouths with side labyrinth seals

Top / bottom seal between transition mouth and 1st row vane endwalls

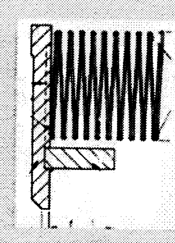
- Advanced transition mouth sealing must:
  - reduce leakage to sustain emission levels, while providing hardware cooling
  - Be robust to survive hostile thermal/vibration environment; and field installation and handling (including periodic transition removal for hardware inspections)

The ATS program includes a systematic approach to improving sealing for static locations. An example is sealing around the exit mouth of combustor transition liners. Leakage at this location is beneficial for cooling adjacent parts, but significantly increases emissions. The two photographs show how sealing is affected in current hardware. The seals are made of heavy metal because of the hostile environment at this location. Also, these parts are robust to allow rugged handling.

Transition mouth bellows seal concept design



Schematic showing bellows seal between transition mouth and fwd of 1st vane row



Cross section of bellows seal

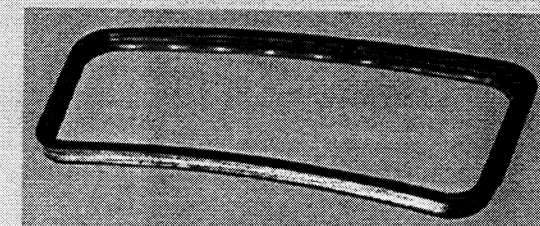
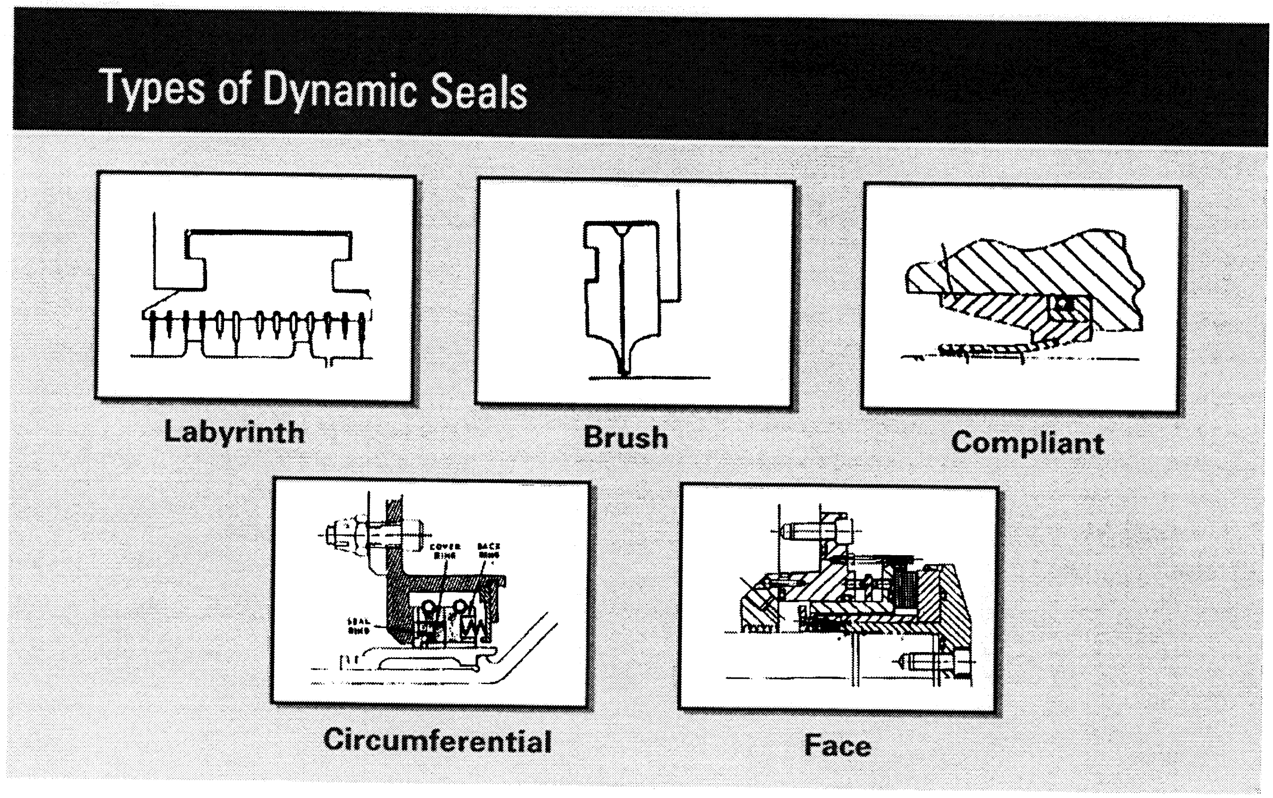


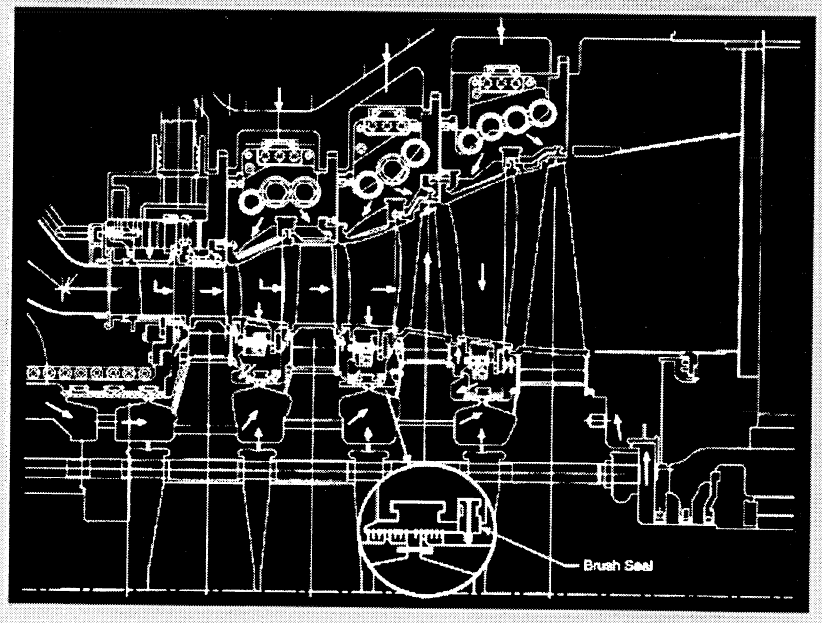
Photo of prototype bellows seal

For the 501ATS, one improved sealing approach being considered is to put a seal around the mouth behind the transition, in front of the vane. The seal shown is a prototype bellows seal built by EG&G for SWPC. It is to be rig tested.



This simple chart shows the various types of dynamic seals. Prime ones include: labyrinth seals; brush seals to replace key labyrinth seals; and a face seal at the rear of the turbine rotor. The latter is needed to meet tight sealing requirements of the closed-loop rotor cooling air system.

501G Turbine Cooling/Leakage Flows



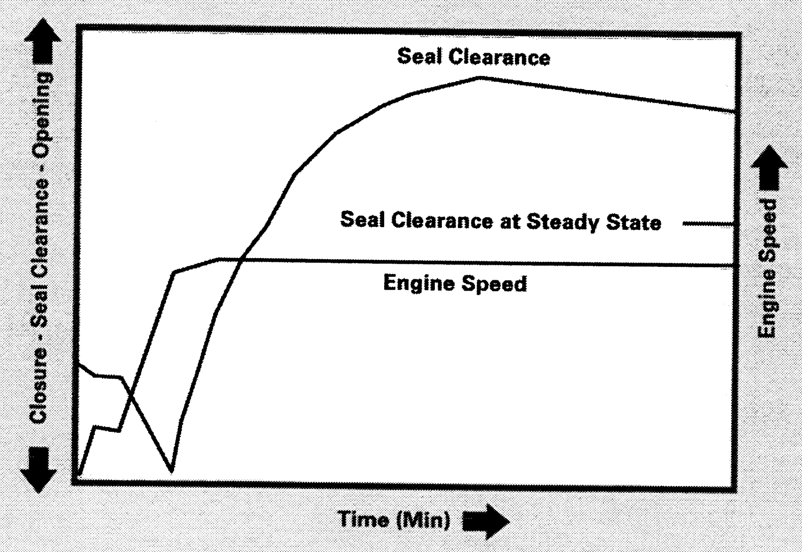
This chart shows a cross section of the Siemens Westinghouse 501G engine. The circle enlargement shows where one of the brush seals is installed. This engine is to be run in the future and the data acquired will be used to demonstrate validity of the brush seal design.

Applying Brush Seals to Industrial Engines

- Requirements:
  - Segmented
  - Durable for handling, etc.
  - Initially installed in series with labyrinth seals
- Challenges:
  - Large radial closures during start up or shut down
  - Long operating life
  - Need to run against uncoated rotor surfaces

The requirements and challenges of installing brush seals include: large closures during startup and shutdown, long operating lives while maintaining low leakage, running against uncoated rotor surfaces, and good handling, durability, etc.

Typical Start-Up Cycle for Brush Seal Locations



- Closure mechanisms
- Pressure, temperature also changing
- Whirl closures not shown

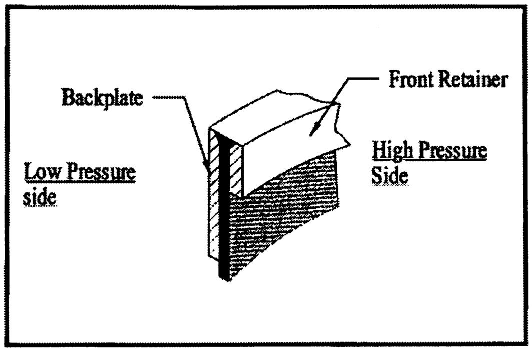
This chart shows a representative startup closure cycle, starting from cold build, then closing initially as the engine speed increases and then leveling off at 3600 rpm for 60 cycle machines and 3000 for 50 cycle ones. The closure decreases to several thousandths and then increases and eventually reaches a steady state level. The challenge with the brush seals for this cycle is at the steady state level is where the seal should run line to line, but eventually will wear line to line at the most closed point. The difference between the minimum closure and steady state minus bristle blow down will be the steady state clearance beneath the bristles.

Brush Seal Development

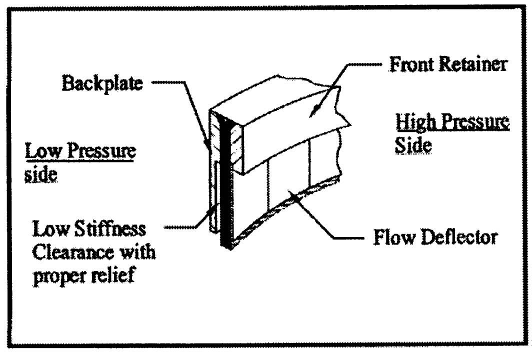
- **Approach**
  - Determine potential seal locations, benefits, etc.
  - Conduct focused development for selected engine locations
  - Validate in service engines
- **EG&G chosen to support focused development efforts**
- **For each development location:**
  - Define operating conditions, requirements
  - Design brush seals to meet requirements
  - Conduct tribology and aero rig testing of candidate seal designs
  - Design full-scale brush seals for validation testing

The approach taken in the ATS program for brush seal development is shown in this chart. EG&G aided in the development. For each seal location, the operating conditions and requirements were defined. This was complicated by not knowing how the engine would be run. For example, the larger new engines are intended for base load operation rather than for peak loads. The brush seal wound not have to experience too many closure cycles. It turns out that the first application may be for peaking with many starts. Or during electrical brown outs, power producers will run their units however they can to produce the most power because of the income possible. They are willing to pay the consequences later. Thus, you need to have margin in the design. Then you design brush seals to meet each engine location requirements rather than design one seal to meet all applications. You may be able to have more universal designs for labyrinth seal, but not with the complex brush seal designs. The development includes tribology testing and aero rig testing of the candidate seal designs, and then full-scale seal design and testing.

Brush Seal Designs



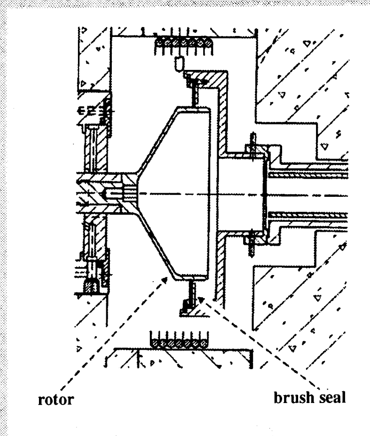
Standard Seal Design



EG&G Advanced Seal Design

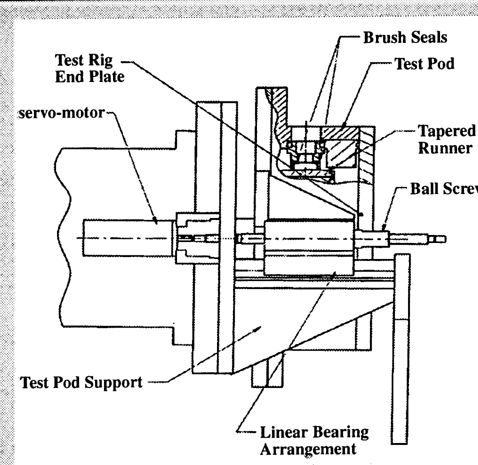
Two basic type brush seal configurations have been considered. One has a standard, generic design similar to brush seals produced by several manufacturers. The other has advanced features developed by EG&G. These features address seal hysteresis and bristle wear. Initial subscale seal testing evaluated the two brush seal configurations for the turbine interstage location. This testing demonstrated feasibility and the advantages of the advanced design. Consequently, only brush seals with advanced features were investigated for the other selected engine locations, i.e., compressor diaphragm, turbine front, and turbine rim.

Brush Seal Testing Approach



Tribology Rig

- Miniature, high speed brush seal rig to conduct accelerated testing
- Temperature, speed, materials, surface condition, contact pressure modeled
- Matrix of bristle alloys and rotor materials/surface conditions tested
- Torque/temperature histories and hardware inspections used to rank bristle/rotor matl's



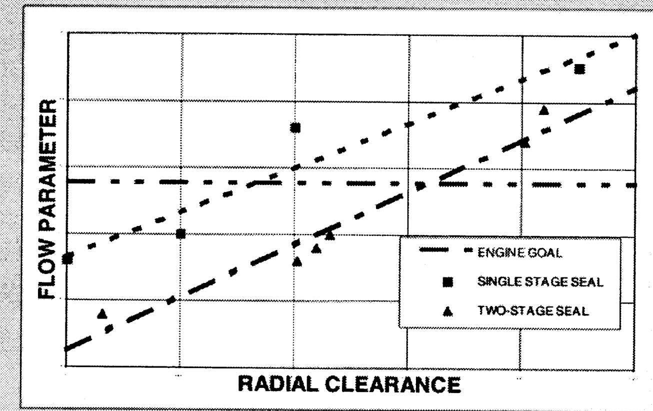
Aerospace Rig

- High speed/temperature rig (1/4 to 1/6 scale)
- Candidate seals tested from design/tribology
- Closure cycle simulated with speed and pressure drop varied
- Steady-state leakage/bristle wear measured
- Borescope viewing of bristle movement
- Static stiffness and leakage also determined

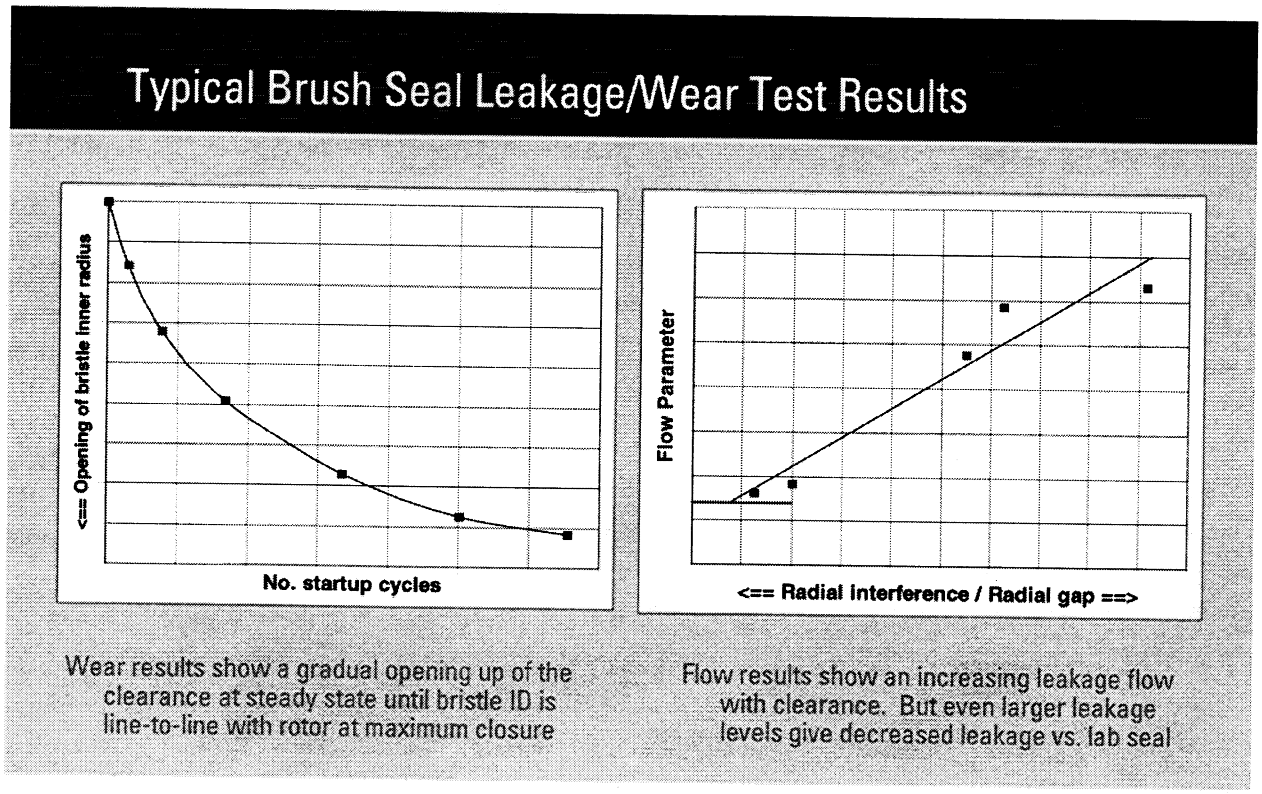
This chart shows the two types of rig tests run at EG&G. The first is a tribology rig to test bristle materials running against uncoated surfaces having different surface roughnesses to determine wear characteristics. Torque characteristics and temperature rises were measured to indicate the wear. Candidate brush seals were evaluated for wear and performance characteristics in EG&G's Aerospace Test Rig. The seals were subscale size with engine pressure drop and rotor speed variations and temperature levels modeled. The rig has been updated to simulate seal closure by providing controlled axial seal movement along a tapered rotor surface.

Turbine Front Brush Seal Rig Results

- Feasibility of a two-stage brush seal demonstrated for the large pressure drop, turbine front location
- Flow characteristics of 1 and 2 stage brush seals determined
- Dynamic character of pressure drop split between two seals determined
- Required clearance to pass desired leakage flow versus overall pressure drop determined



This chart shows results for the turbine front brush seal. It was desired to put a two-stage seal in this location because of the high pressure drop. In the testing, both single- and two-stage seals were evaluated. For the two-stage seal, it was desired to measure the dynamic character of the pressure drop between the seals since the seals are not fixed orifices. The horizontal line indicates the desired leakage flow rate to provide purging of a downstream disk cavity. The results indicate the required clearance beneath the brush seals for one- and two-stage seals.

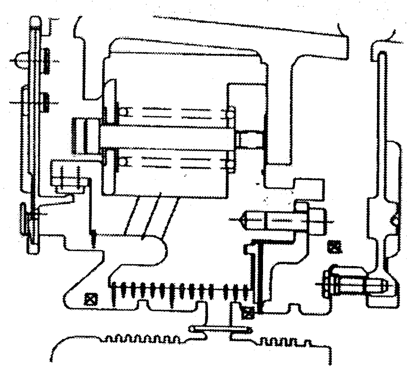


This chart shows the basic concept of how seals wear. For example during the startup cycle, a maximum amount of interference compared to steady state would be the height in the left-hand plot. This plot could also represent the number of steady state hours with a fixed interference. The result is an expected exponential wear decay curve. On the right side is the flow parameter versus radial interference/clearance. For interferences, the leakage flow parameter is nearly constant. For clearances the line is nearly linear with gap. The gap shown is for zero pressure drop across the seal. For pressure drop conditions, the bristles will blow down toward the rotor, so the slope of the line reflects an area change with pressure drop.

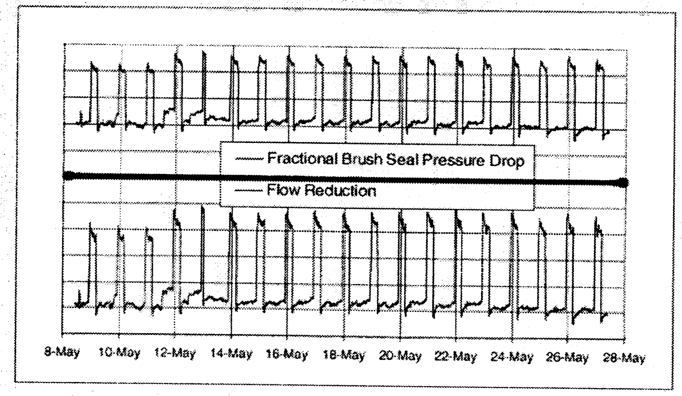
Validation of Brush Seals in Combustion Turbines

- Brush seals installed in 501D5, 501F, 501G (in turbine interstages)
- Brush seals at several locations in the 501ATS being designed

Typical Engine Data for 501D5 Turbine Interstage Brush Seal



Pressure tap locations



Brush seal performance showing effect of varying load

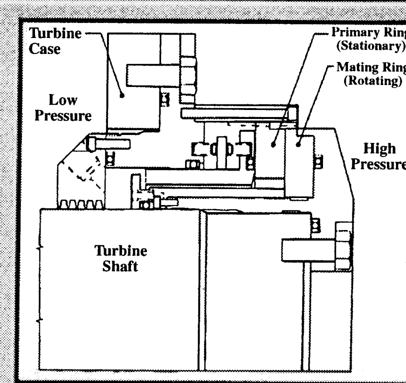
This chart shows field data acquired recently for a brush seal installation. The instrumentation included pressure taps upstream of the labyrinth seal, between the labyrinth and brush seal, and downstream of the brush seal. The y axis for the upper curve is the fraction of the total pressure drop across the brush seal. These data are for over several days without an intervening shut down. At night the load to the unit is reduced causing the steps in the plot. These steps are caused by changes in the air temperature from part to full load, which in turn causes a different clearance beneath the brush seal. The fractional pressure drop data are used to calculate the flow reduction due to the brush seals as shown in the lower plot. This calculation is possible from the known flow characteristics of the labyrinth seal. Thus, the labyrinth seal provides a measurement device. The actual flow reduction can be calculated from an assumed clearance. Results from these calculations showed a significant leakage flow reduction due to adding the brush seal.

501ATS Rotor Rear Seal Development

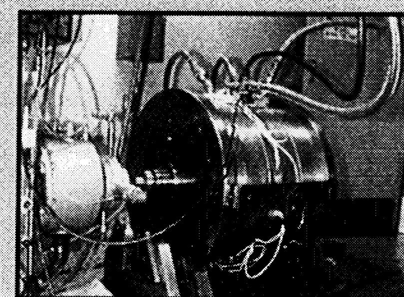
Requirements
- Low leakage
- Large axial movement
- High pressure drop
- Robust, long life with part time low speed operation
- Handle particles in leakage air
- Smaller dia., not necessarily segmented

Selection
- Vendor - John Crane Inc.
- Seal - Non-contracting, dry running gas lubricated end face seal - hydrodynamic type
- Design - based on current Crane Type 28 seals with modifications to meet requirements

Evaluation
- Long life with part time low speed operation
- Large axial movement
- Proper installation/durability capability
- Handle air contamination



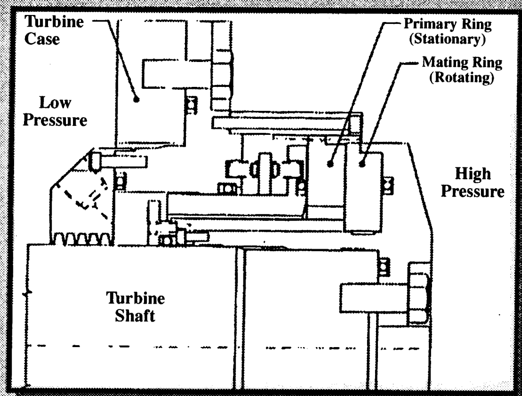
Rotor rear seal schematic

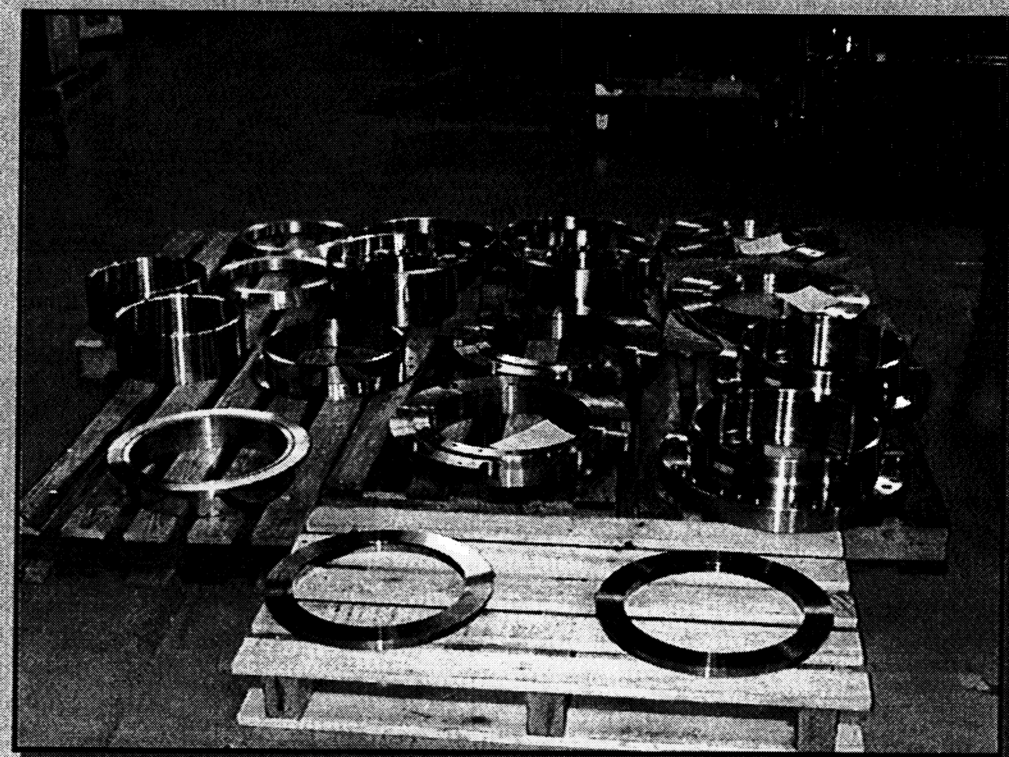


John Crane test rig to simulate engine conditions

A separate development effort focused on providing very low leakage of cooled compressor discharge air as it enters the 501ATS rotor at the rear. John Crane Inc.'s spiral groove face seal technology was adapted to this location with larger diameter and axial movement than in previous applications. Rig testing has been done to verify the seal's design and low leakage over a range of engine operating conditions. This chart shows a cross section of one of Crane's seals. There are several issues to address: the air to be sealed needs to be free of particles above a certain size, the axial movements are large, the swash level is high, the expected operation hours is high, and there will be times when the engine is not running that the rotor will be rotated at slow speed on a turning gear with no pressure drop across the seal. The latter was evaluated by including a special test at low speed.

Rotor Rear Seal Design and Hardware Prior to Assembly



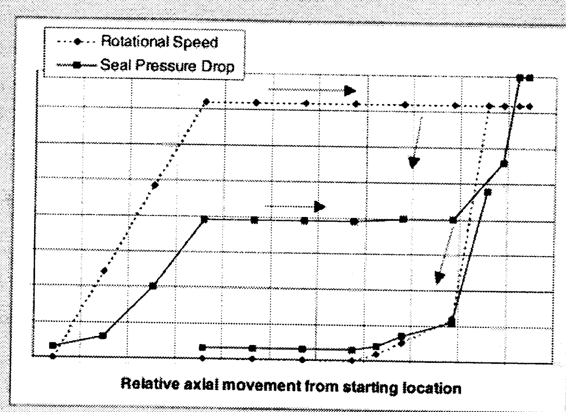


This chart shows a photo of unassembled hardware for two rotor rear seals. Two seals were required for the test set up.

Rotor Rear Seal Rig Testing

Tests Performed:

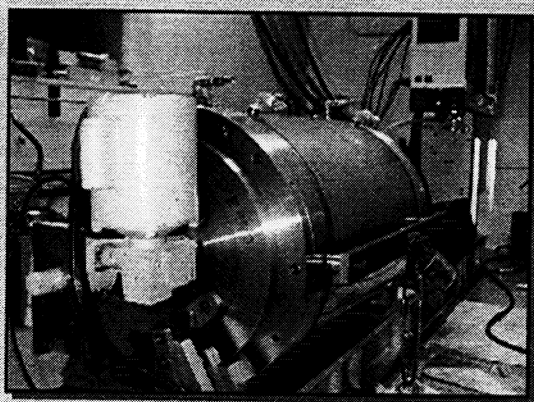
- Performance testing
  - With simulated operation cycle
  - Large axial travel evaluations
  - Angular misalignment
  - Leakage & wear assessed
- Over-speed spin testing
- Extended turning gear operation



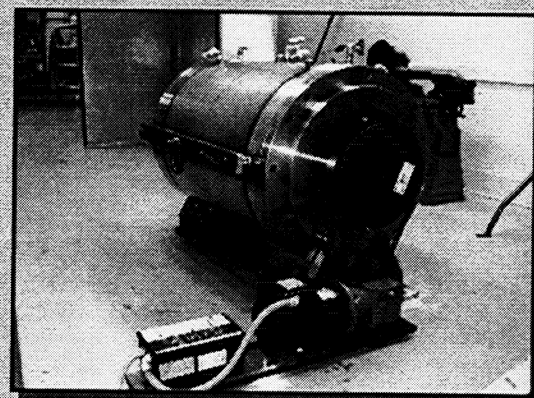
Simulated operation cycle

This chart lists the various tests performed and the engine start-up/shut down simulation cycle used to evaluate seal performance and leakage.

Rotor Rear Seal Rig Test Pods

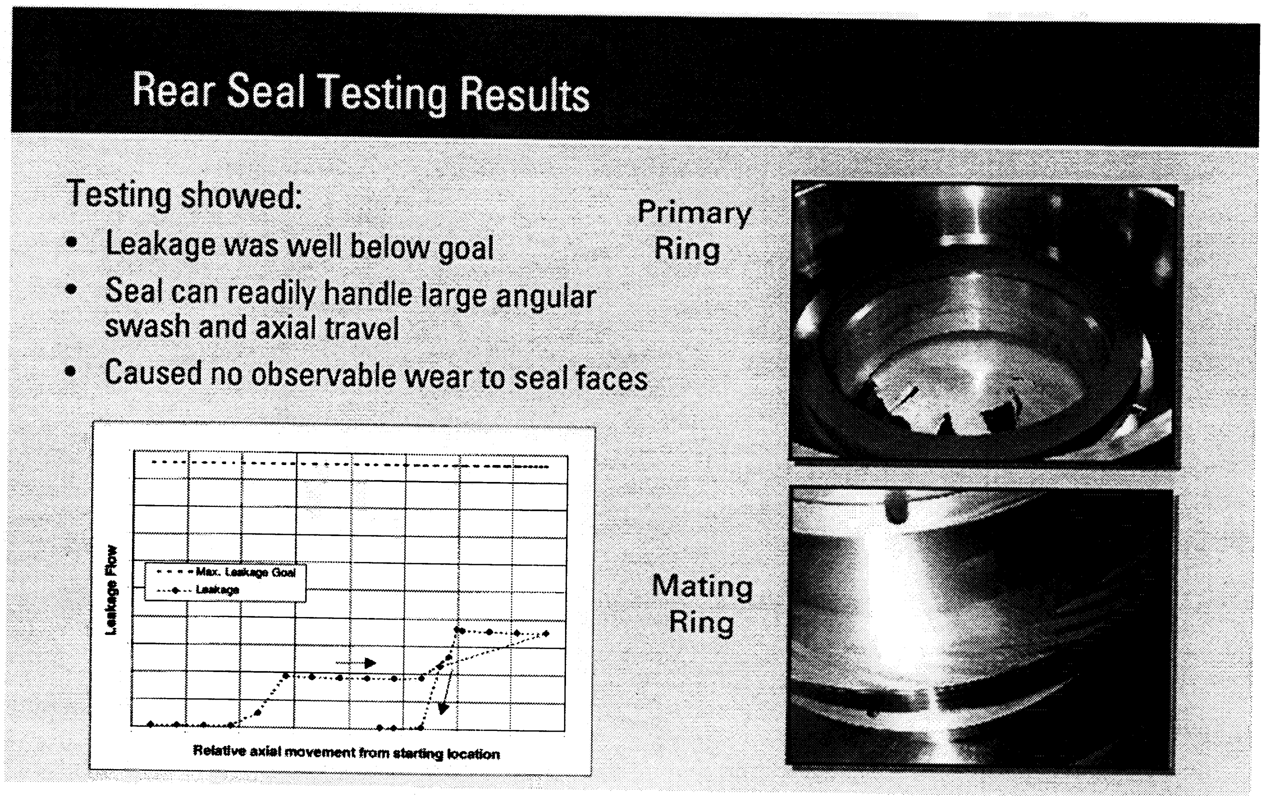


Test pod used in performance testing
with axial stepping motor mounted



Turning gear test arrangement

The left-hand side of this chart shows the test pod used for the performance testing. The motor in the foreground was a new addition to Crane's test rig to provide axial movement during operation. The right-hand side shows the test arrangement for the low speed testing.



Test results for the rotor rear seal showed that the leakage was well below the goal. This goal is significantly below what a labyrinth or brush seal could provide. Thus, spiral-groove face seals are indeed very low leakage devices. Post-test inspection of the seal faces showed that there was no observable wear, not even minor scratches. After the very successful testing, the two seals are awaiting installation into a 501ATS engine.

Summary

- Improved sealing in large combustion turbines has significant payoff in increased efficiency, reduced emissions, maintaining RAM
- Static seals are improved by adapting/advancing proven concepts
- Dynamic sealing improvement has focused on developing brush seals for turbine interstages, rims, and front; and compressor diaphragms
- Focused brush seal development is complete for the turbine interstages and compressor diaphragms;
- Full-scale turbine interstage brush seals are being validated / commissioned in several CT's.
- Non-contact, dry-gas, spiral-groove face seal has been designed, fabricated, and rig tested for the 501ATS rotor rear

In summary, advanced seal has a significant payoff—much more that the added costs to implement the new seal hardware. Further, very few units need to be sold, before the R&D costs can be recovered.

COUPLED, TRANSIENT SIMULATIONS OF THE INTERACTION BETWEEN POWER AND SECONDARY FLOWPATHS IN GAS TURBINES

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CFD Research Corporation
Huntsville, Alabama

and

Robert Hendricks and Bruce Steinetz
NASA Glenn Research Center
Cleveland, Ohio

OUTLINE

- **Overview and Objectives**
- **Coupling Methodology**
- **Description of Codes, Interface Algorithm**
- **Sample Cases, Results**
- **Summary**

NEED FOR COUPLED ANALYSIS

- Multi-Stage Compressor and Turbine Section Present in Gas Turbines
  - interstage cavities necessary
  - powerstream/mainpath/primary flow: flow above blade platforms
  - secondary flow refers to flow under blade platforms

- Mainpath-Secondary Flow Interact Strongly; can Affect
  - efficiency and power performance
  - component life

- Higher Efficiency and/or Power Requires
  - details of mainpath, secondary flows
  - design, off-design and transient conditions

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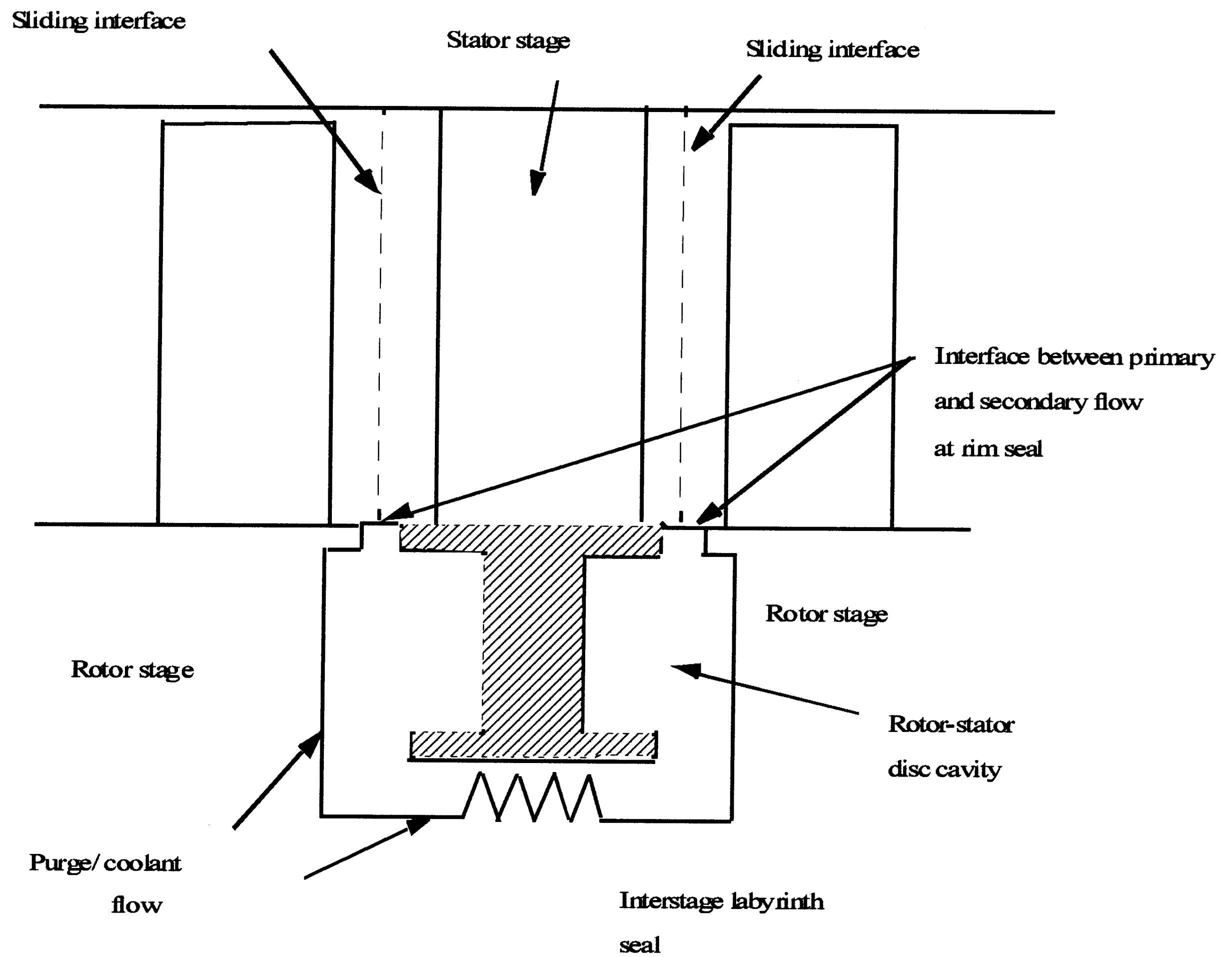
PRIMARY-SECONDARY COUPLING SCHEMATIC



- Rim Seal Details Change in Compressor and Turbine Sections
- Requirements of Leakage/Ingestion/Coolant also Change

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SECONDARY FLOW REQUIREMENT

- Interaction between Primary-Secondary Flow has Different Aspects in Compressor and Turbine Sections

- Compressor Side: Minimize Leakage Flow
  - reduce recirculation, windage losses
  - reduce effects of re-introduction in mainpath
  - affects performance

- Turbine Side: Much More Stringent Requirement
  - mainpath gas ingestion: avoid at all costs
  - coolant flow is a must, but represents efficiency loss
  - optimization of coolant flow requires much more careful attention to transient flow details

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OBJECTIVES OF PRESENT METHODOLOGY

- To Develop a Validated Set of Codes for Coupled, Transient Solutions of Primary and Secondary Flows in Multi-Stage Machines
  - use existing validated codes for different streams: SCISEAL for secondary; MS-TURBO for primary
  - develop interfacing algorithms for coupling the codes
  - graphical user interface for ease of use

- Use of Separate Codes
  - widely different flow physics in primary and secondary flows
  - validated codes available, specifically developed for each flow stream
  - capabilities offered by the combinations

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CURRENT METHODOLOGIES RECAP

- **Single Simplified Cavity Flow**
  - experiments, analytical, simplified models for cavity flows

- **CFD Flow and Heat Transfer**
  - 2-D axisymmetric , steady-state
  - complex cavity shapes, heat transfer, some measure of interaction between mainpath-secondary

- **3-D CFD: Analysis**
  - steady and unsteady solution in compressor (Allison Group)

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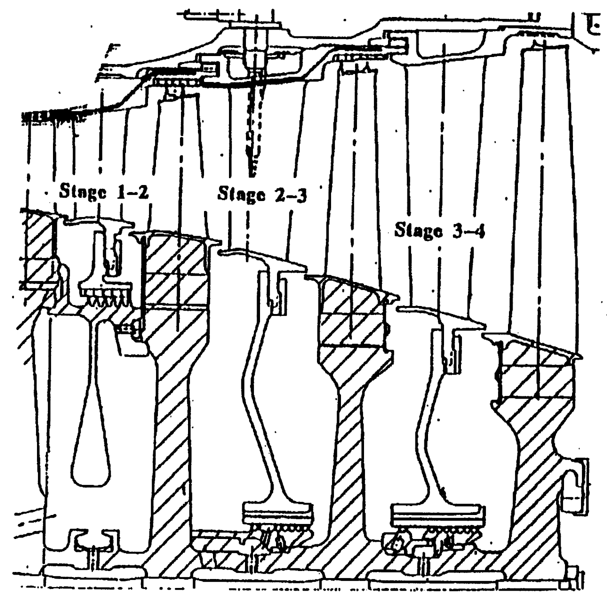
PROPOSED COUPLED CODE METHODOLOGY

Power Stream

TURBO: density based, finite volume, structured grids, time-accurate, multiple blade rows, high speed flows

Interface



Cavity/Secondary Flow

SCISEAL-U: pressure based, finite volume unstructured, adaptive Cartesian grids, time accurate, conjugate heat transfer, turbulence, low speed flows

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DESCRIPTION OF SCISEAL CODE

Salient Features

- Unstructured Grid Topology with Mixed Elements (quads, prisms, polyhedra), Adaptive Cartesian Grid Capability
- Fully Implicit Pressure-Based, Finite Volume
- Cartesian Velocities, Non-Staggered Arrangement
- Sequential Solution Procedure with SIMPLEC-M for Velocity-Pressure Coupling
- Conjugate Gradient Solvers for Linear Systems
- Flow, Conjugate Heat Transfer, Turbulence
- Links with Grid Adaptor for Solution-Based Adaptation

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DESCRIPTION OF TURBO CODE

UNCLE_TURBO Applications Group

- **Developed for Predominantly Axial Flow Rotating Machines**
  - multiple blade row, fans and propellers (ducted and unducted)
  - multistage compressors and turbines (no chemistry yet)
  - rotating/stationary asymmetric configurations with appendages
  - helicopter rotor (hover configuration)
  - complete airframe - propulsor integration

- **Developed for Unsteady Flow Analysis**
  - uneven blade count, unsteady, nonlinear complex flow
  - combined internal and external flow
  - non-axial inflow conditions
  - inviscid or viscous flows

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CODE COUPLING/INTERFACE ISSUES

- Solution Methodology of the Codes
  - primary variables, flux calculation, turbulence, boundary treatment, internal memory management, ...
- Coupling Level
  - data exchange frequency, data type
- Interface Placement at Rim Seal
- Interpolation Code(s) for Data Transfer from One Code to Other

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CURRENT INTERFACE STRATEGY

- Placement of Interface at Rim Seal

- Coupling Level
  - both codes perform subiterations at each time step
  - data exchange after several subiterations of each code

- Data Type to be Exchanged
  - variables from SCISEAL (ρ,ρu, ...) interpolated to ghost layer in TURBO and used directly
  - TURBO fluxes at interfaces interpolated to SCISEAL interface and used directly
  - fluxes at interfaces matched and maintained

- Timesteps Determined by TURBO based on relative speeds of Rotor and Stator Elements, and Mainpath Grid Size

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COUPLED FLOW SIMULATIONS

Test Cases Computed/In Progress

1. Validation/Checkout Case
   - angular "mainpath" with disc cavity
   - allows single-code (SCISEAL) and coupled runs
   - solutions compared to validate

2. H.P. Rig by UTRC
   - single stator and rotor vane with cavity
   - coupled simulations to be compared with data

3. NASA Low-Speed Air Compressor (LSAC) Facility
   - 3rd rotor + 4th stator + 4th rotor in mainpath
   - associated disc cavity with 1 tooth labyrinth seal

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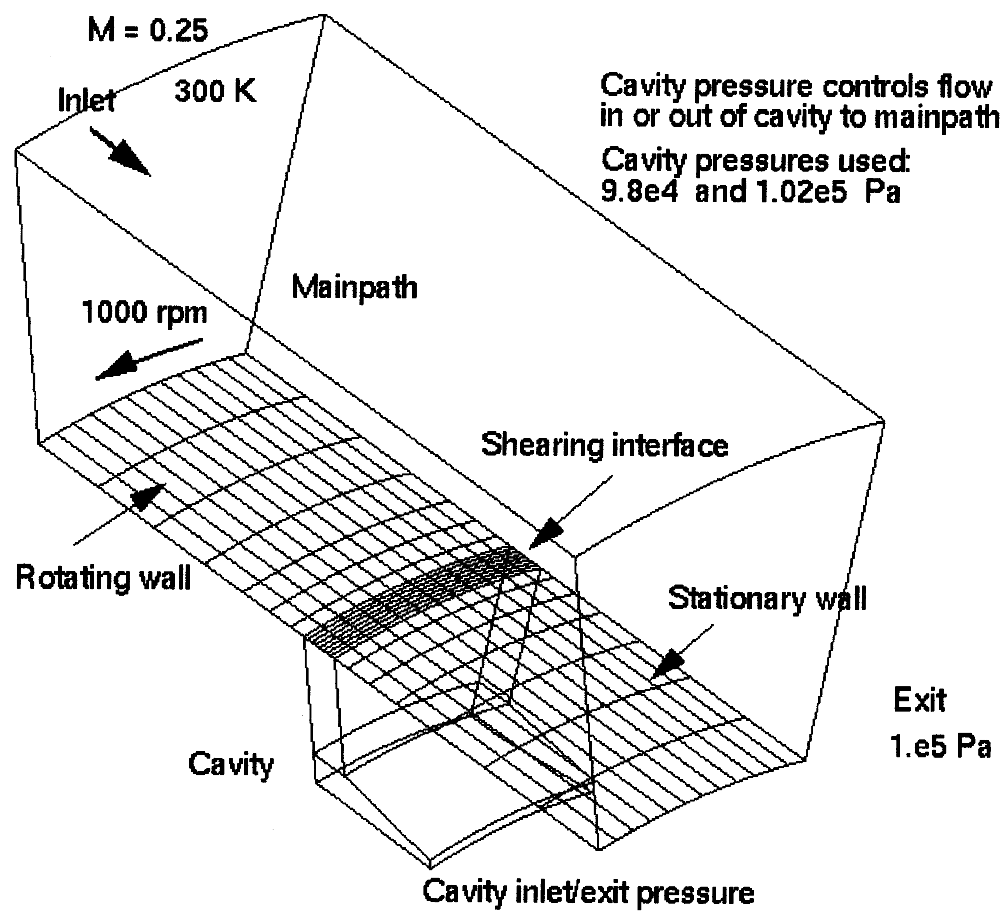
ANNULAR FLOW CASE

- Checkout/Validation Case
- Problem Definition and Boundary Conditions



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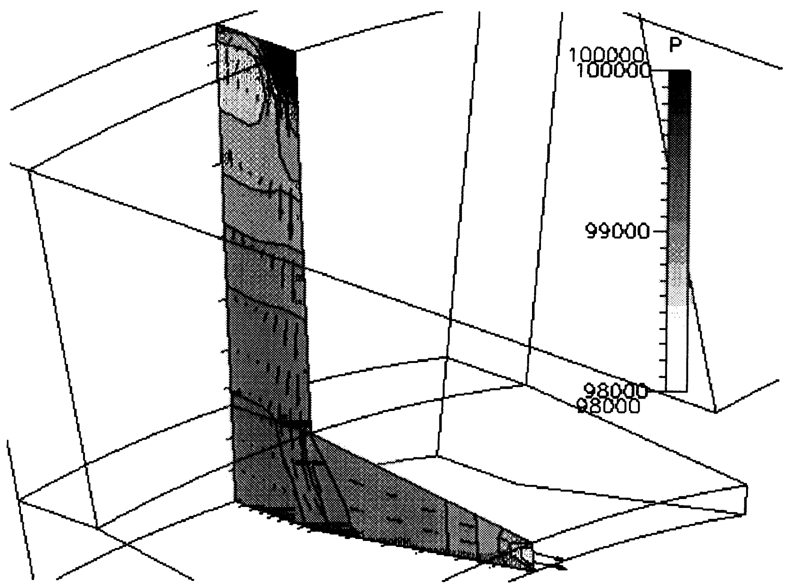
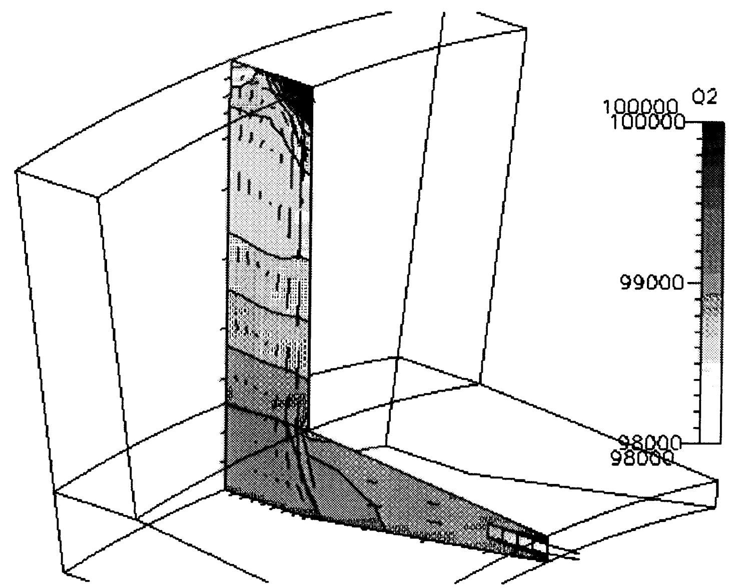
COMPARISON OF RESULTS

Cavity Flow with Ingestion in Cavity



single code
SCISEAL



coupled codes
SCISEAL-TURBO

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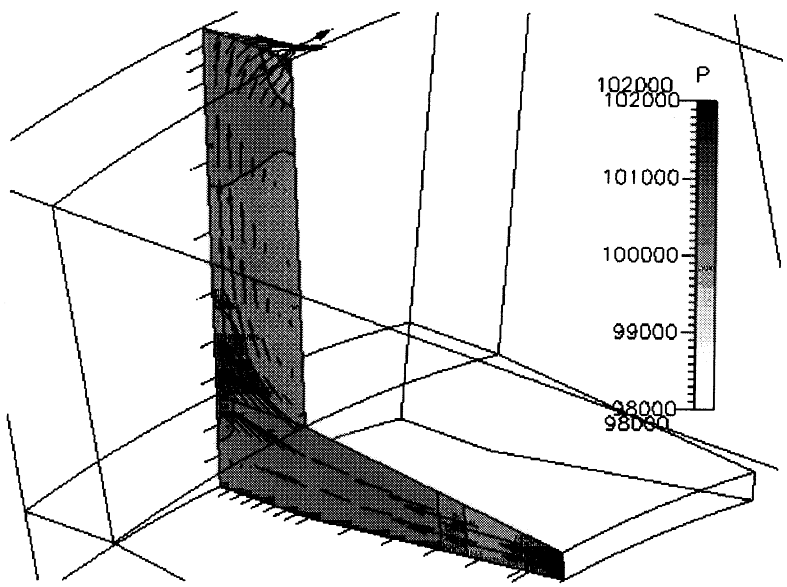
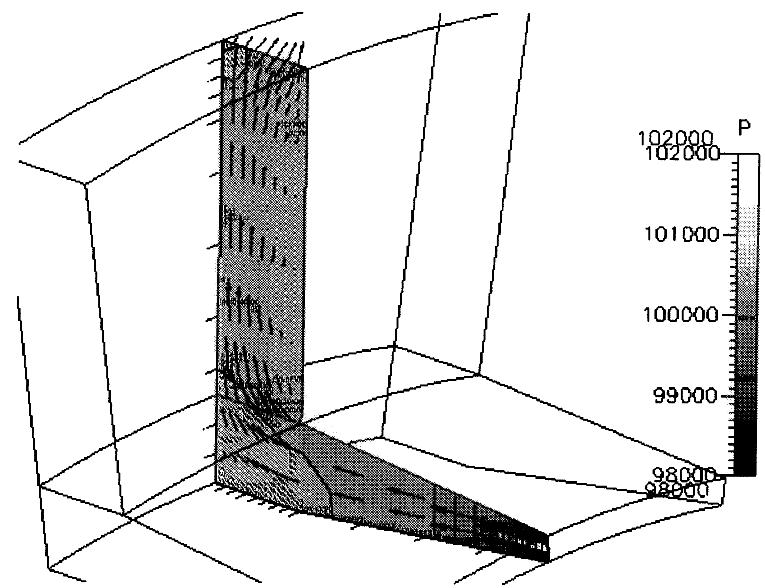
COMPARISON OF RESULTS

- Cavity Flow with Flow Out of Cavity
- Flow Rates from Coupled Runs Match to Within 10% of the Values for Single-Code Runs (outflow velocities differ due to graphical post-processing)



single code



coupled codes

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H.P. RIG UTRC

- Single Stator and Rotor Stage;
  High-Work Design

- 48:58 Blade Numbers, Changed to 48:60;
  Allows a 30° Sector for Flow Calculations

- 4 Blades in Stator, 5 Blades in Rotor
  - 49x12x15 grid in each stator blade passage
  - 36x12x12 grid in each rotor blade passage
    (total ~ 61K cells)

- Cavity + Rim Seal: 16 domain multi-block grid
  - all flow areas modeled exactly
  - 33000 cell grid

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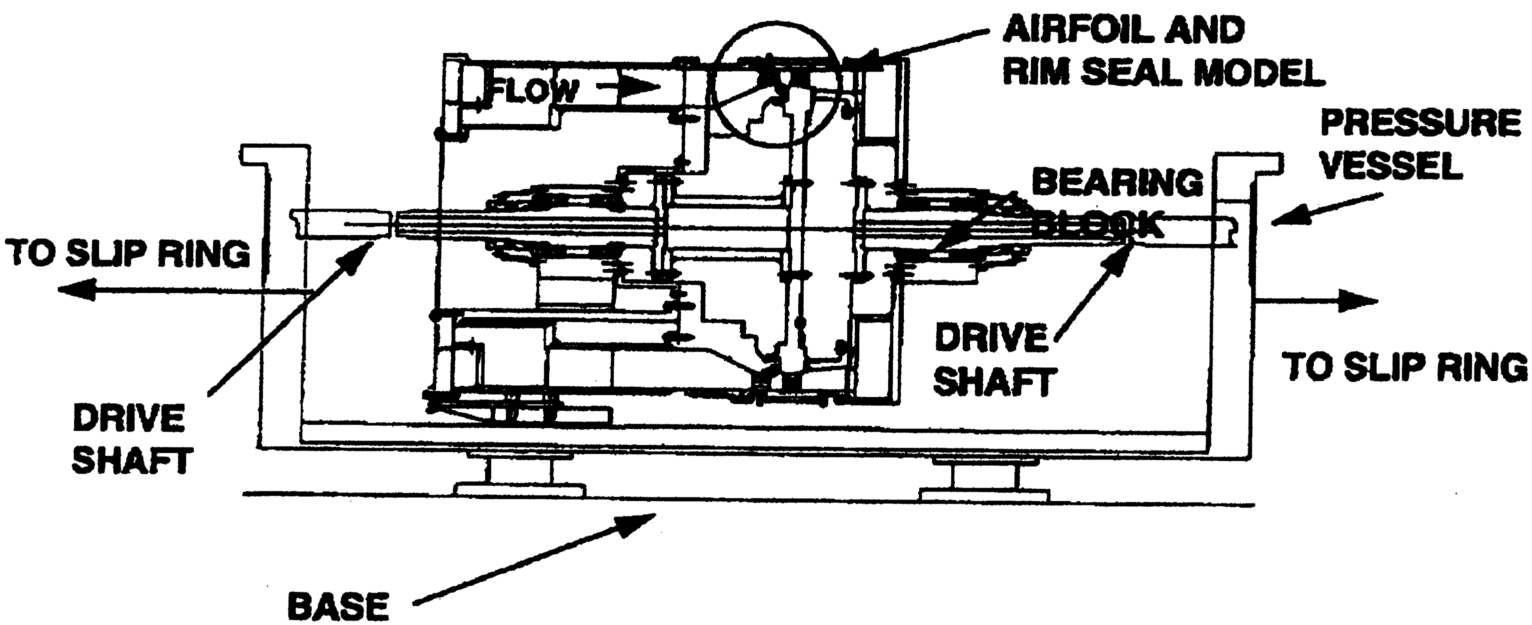
SCHEMATIC OF THE H.P. TURBINE RIG

CROSS-SECTION OF RIM SEAL INGESTION RIG



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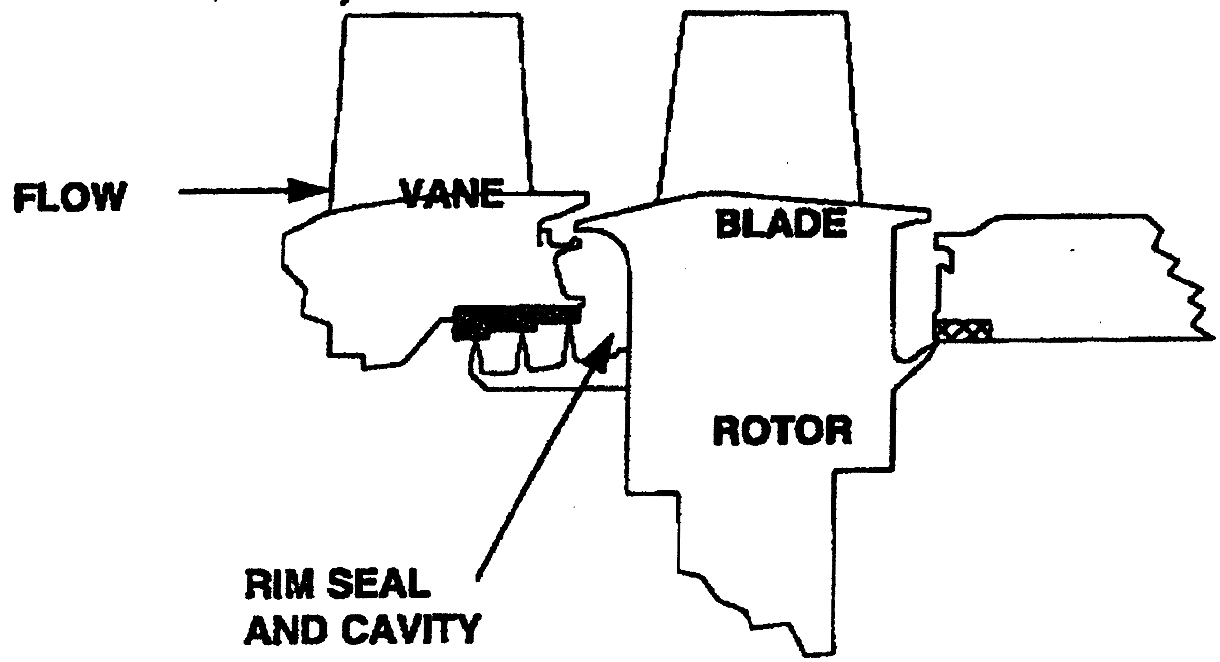
DETAILS OF THE FLOWFIELD IN H.P. RIG

VANE, BLADE AND RIM SEAL MODEL



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H.P. RIG

- Main Path Condition

  - Upstream pressure: 155 kPa (22.4 psia)
  - Temp = 302.6K (544.6R)
  - $\dot{m}$ = 5.766 Kg/s, axial flow

- Downstream Pressure = 122.7 kpa (17.8 psia)

  - 3600 rpm

- Cavity Inlet Conditions (2 Considered)

1. Total pressure = 150.35 kPa (0.97 P_{upstr}), T = 302.6K
2. Total pressure = 124 kPa (0.80 P_{upstr}), T = 302.6K

Case 1 shows Egress from Cavity
Case 2 Nearly Zero Flow Across Rimseal

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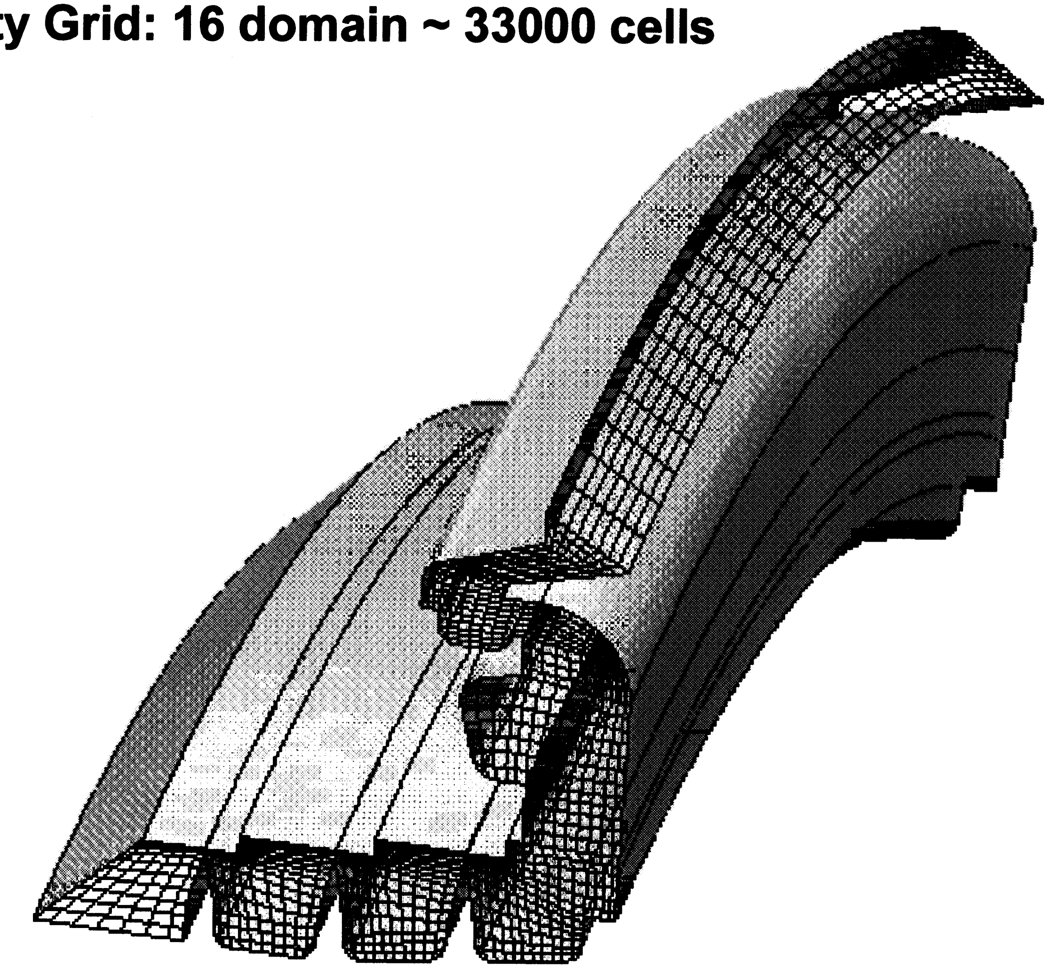
H.P. RIG

- Cavity Grid: 16 domain ~ 33000 cells



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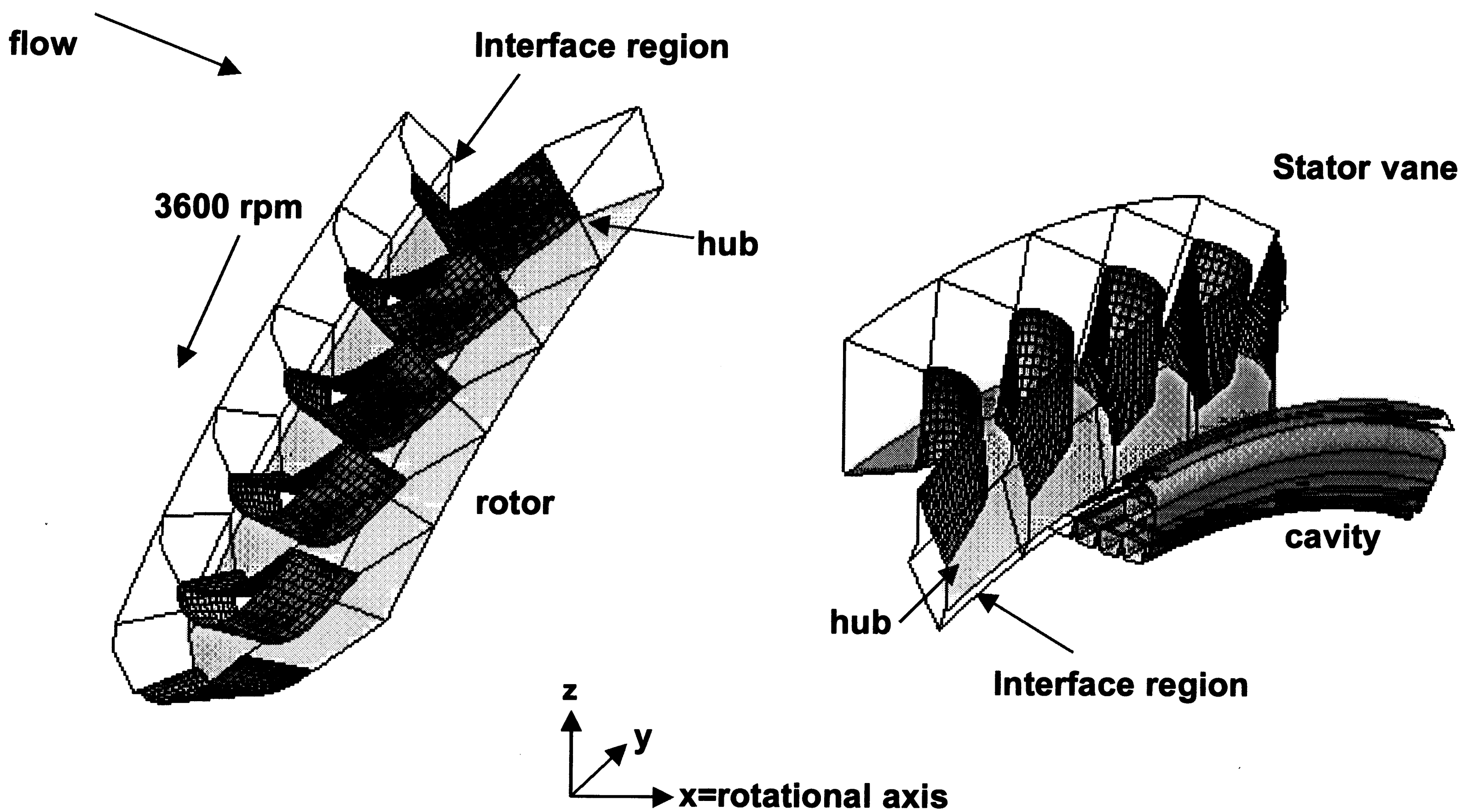
H.P. RIG

- **Relative Locations of Flow Domains at a Specified Time Instant**



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H.P. RIG SIMULATIONS

- 2D Axisymmetric (No Blades in the Main Path, Steady-State) and 3D Coupled, Transient Runs Simulated

- Rim Seal has Net Flow Entering the Mainpath (for Case 1)
  - 2-D: 0.276×10^{-3} Kg/s per 30° sector
  - 3-D: $0.25\text{-}0.26 \times 10^{-3}$ Kg/s per 30° sector

- Results for Case 1:
  - taken after about 600 steps
  - vector plots: in cavity at different cross-section, 2-D results, mainpath
  - static pressure: in cavity, at hub in mainpath

- Results for Case 2:
  - cavity velocity and pressure fields at similar locations

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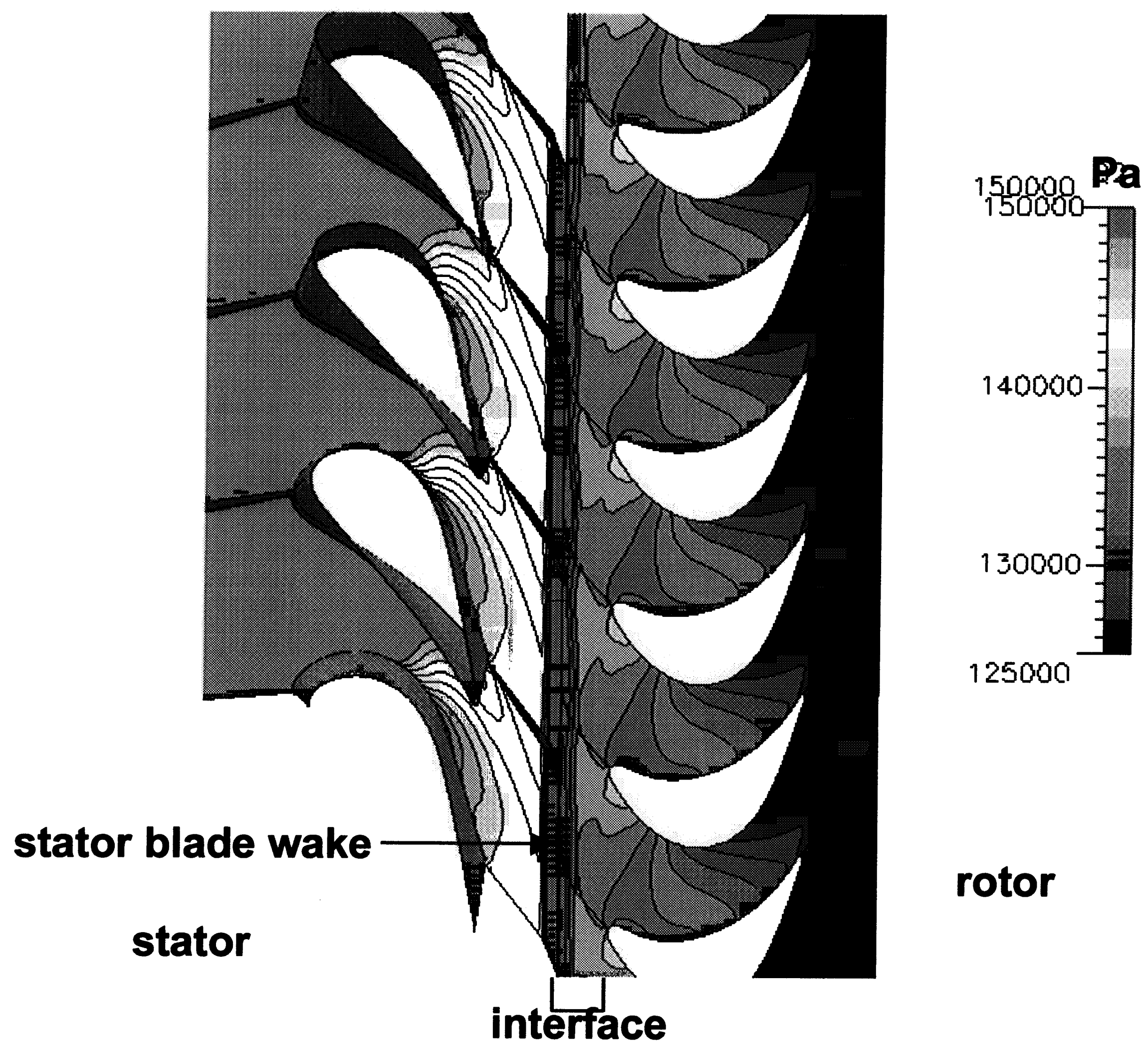
MAINPATH SOLUTIONS

Static Pressure Field at Hub



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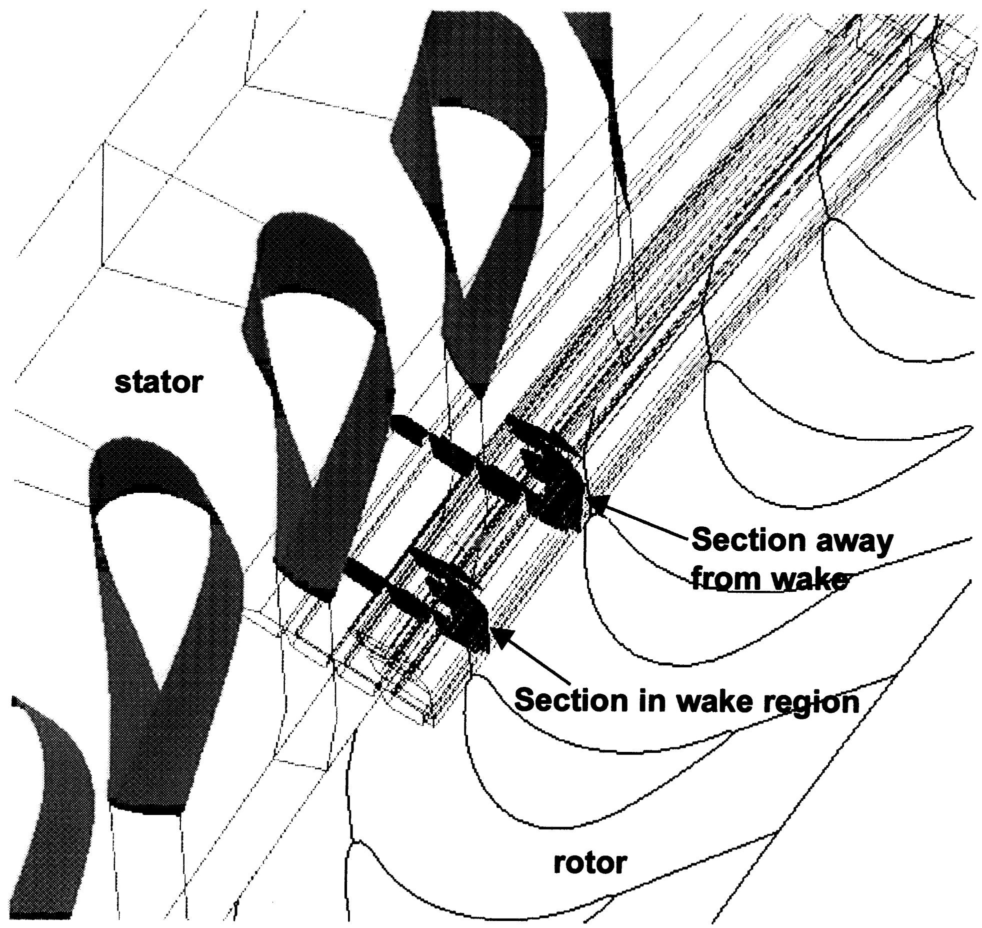
CAVITY FLOW

- Locations of Cavity Cross-Sections



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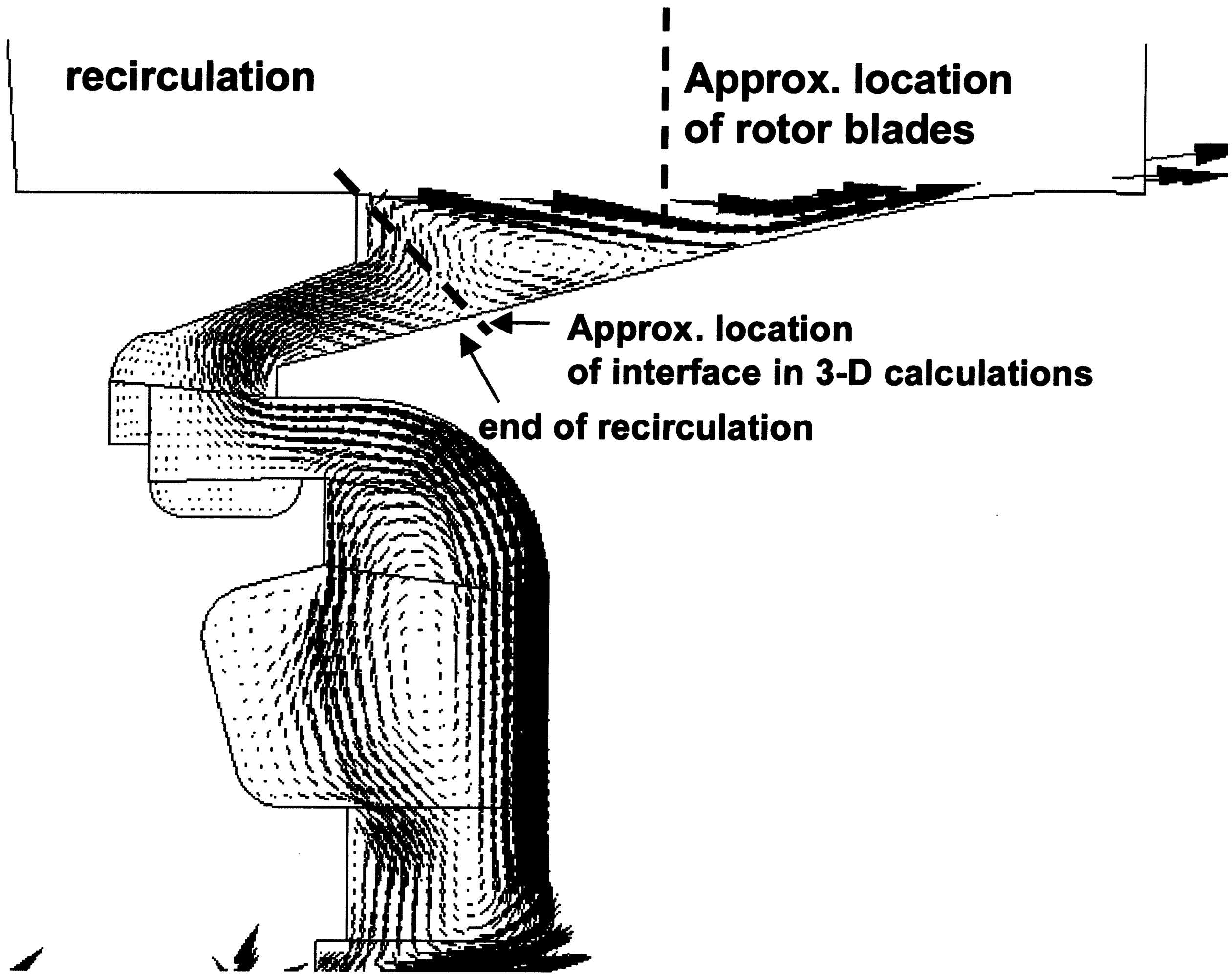
CAVITY VELOCITIES

2-D Axisymmetric, Steady-State Field, Case 1



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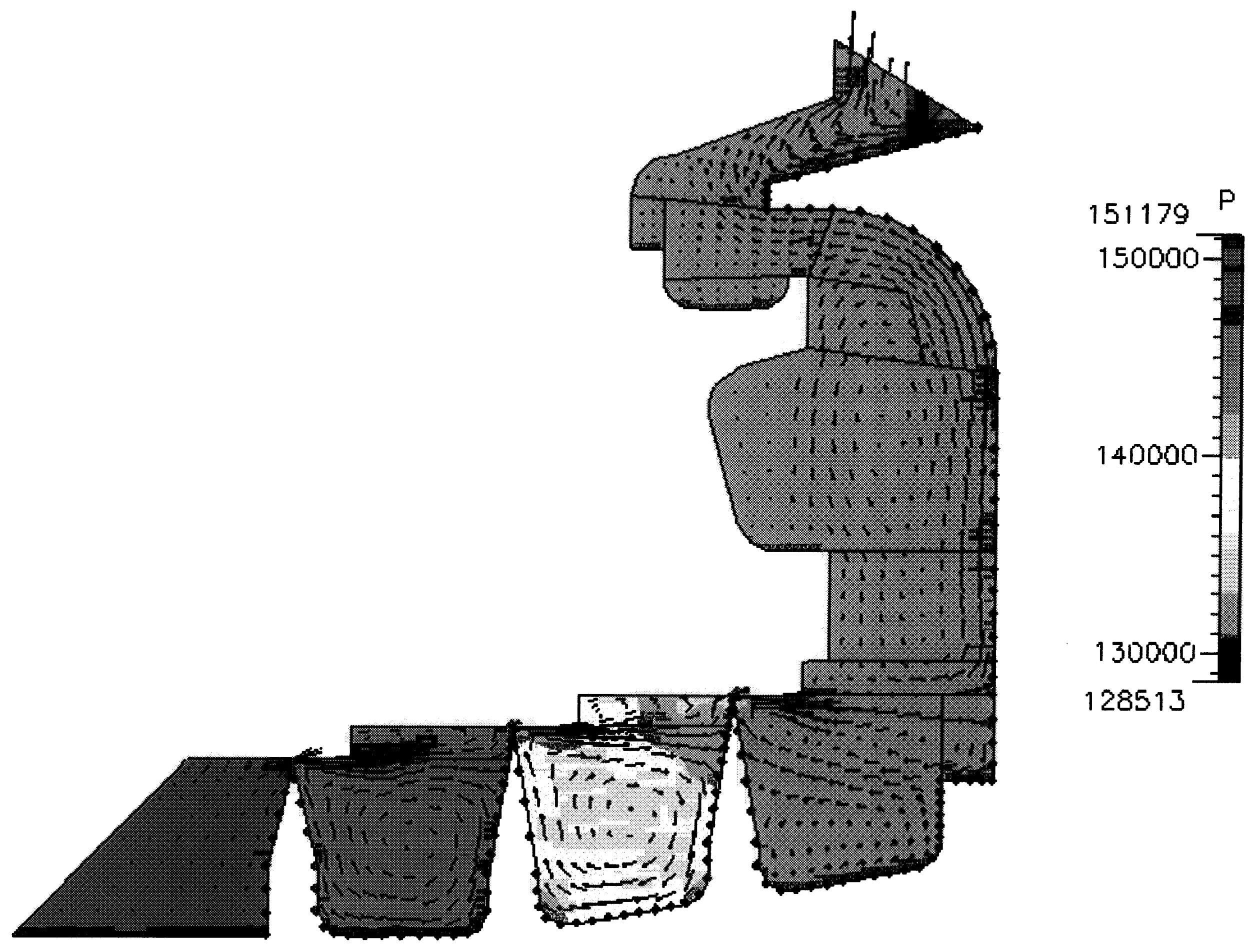
VECTOR PLOTS IN CAVITY

- **Rim Seal in Slow Moving Mainpath (Blade Wake), Case 1**



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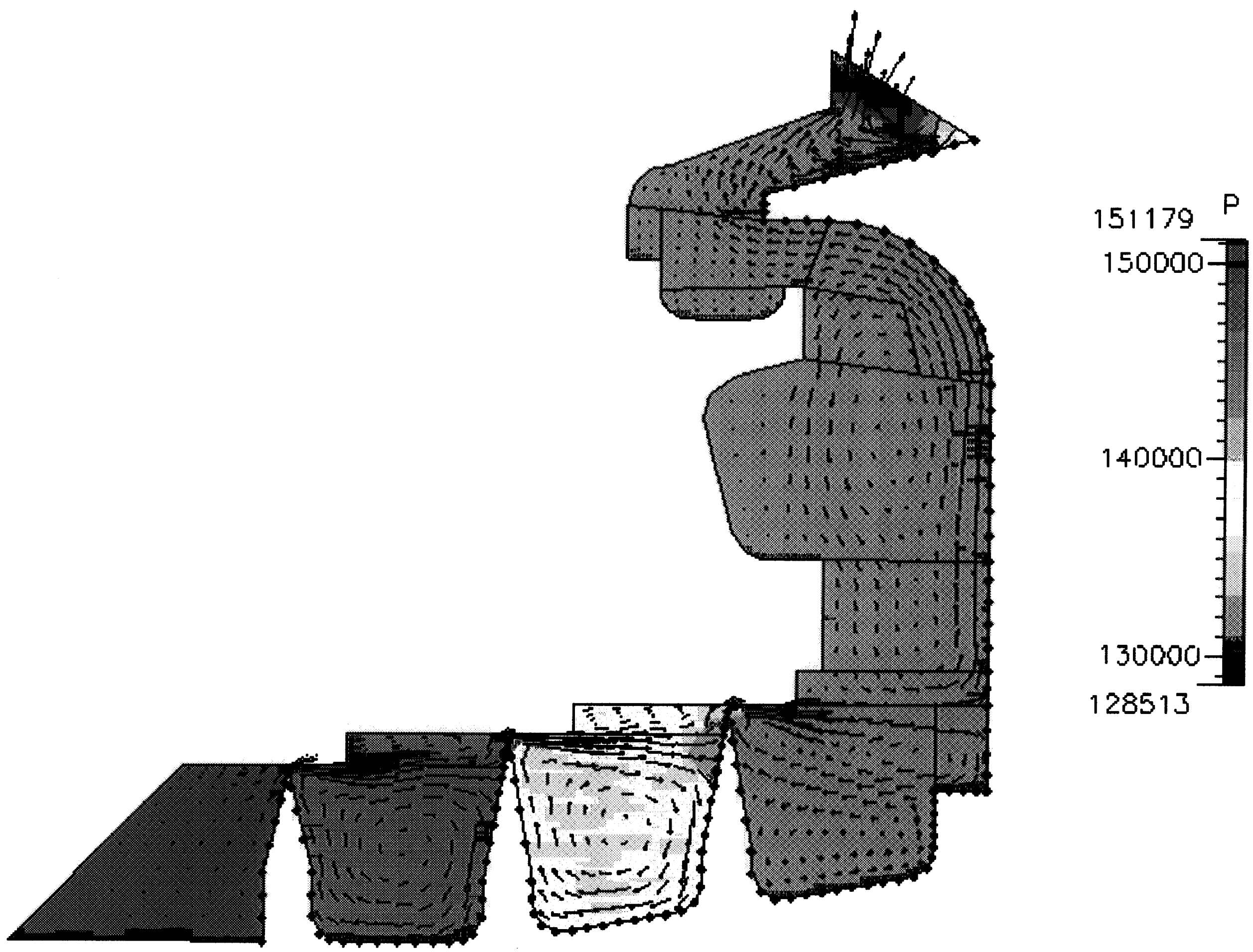
VECTOR PLOTS IN CAVITY

- 3-D, Coupled Solutions, Case 1
- Rim Seal in Fast Moving Mainpath Flow Area



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LSAC RIG

- Low Speed Compressor Facility in NASA LeRC

- Simulation Involve 3rd and 4th Rotor Stages + Stator 3 and Associated Cavity
  - experimental data available for comparison (Wellborn and Okiishi, 1996)

- Validation Case for Coupled Codes

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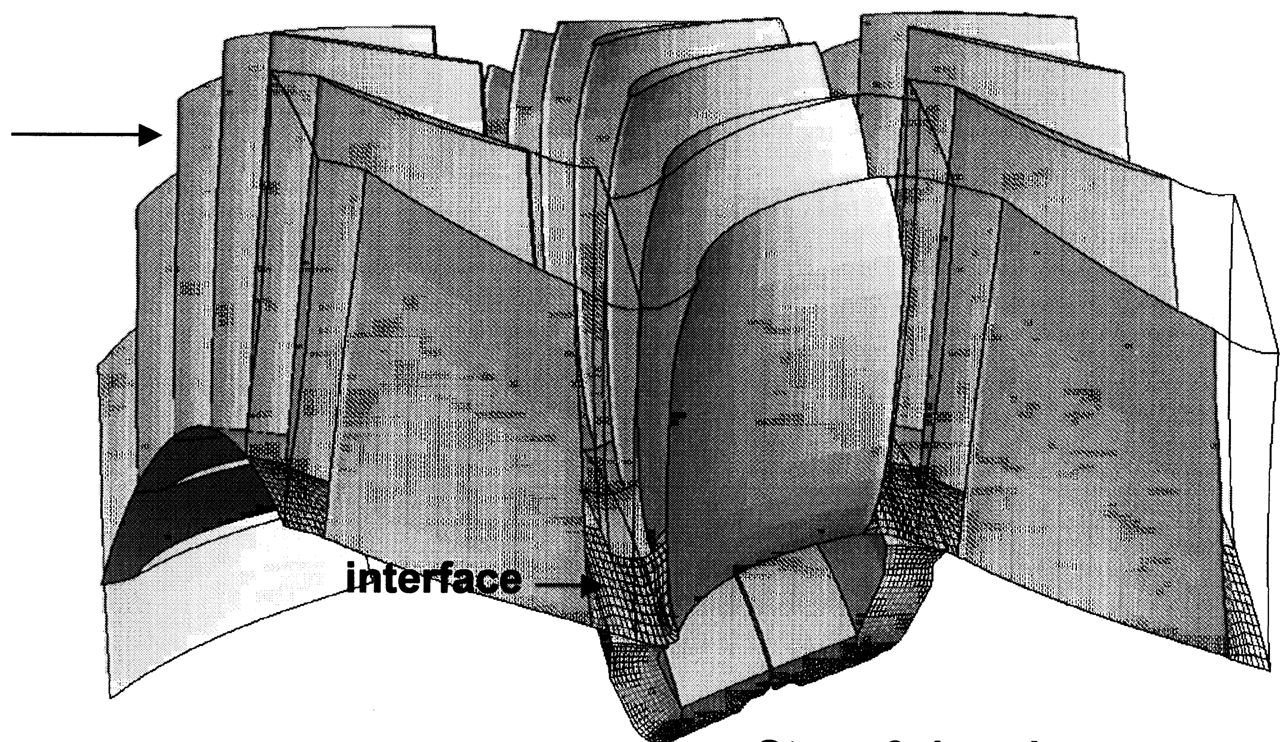
LSAC FLOW DOMAIN

- 2 blade rows + 1 vane (stage 3, 4 blade rows, stage 3 vane) + interstage cavity



Flow geometry

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LSAC RIG

- 3 Blade Passages for Rotor 3 and 4, 4 Passages in Stator
  - pi sector with 360/13 degrees
- Grid Sizes: 130K cells in Mainpath, ~ 28K in Cavity
- Mainpath Boundary Conditions:
  - specified profiles of Po, To,flow angles at inlet
  - pressure ratio (static) of 1.02 across 2 stages
  - rotor speed = 958 rpm
- Cavity Boundary Conditions
  - appropriate stationary and rotating walls
  - rimseal conditions are part of the solution

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LSAC RIG

- Solution in Progress
  - very low speeds in mainpath present some difficulty

- Calculated Mainpath Flow Rates Yield Flow Coefficient ϕ of 0.34

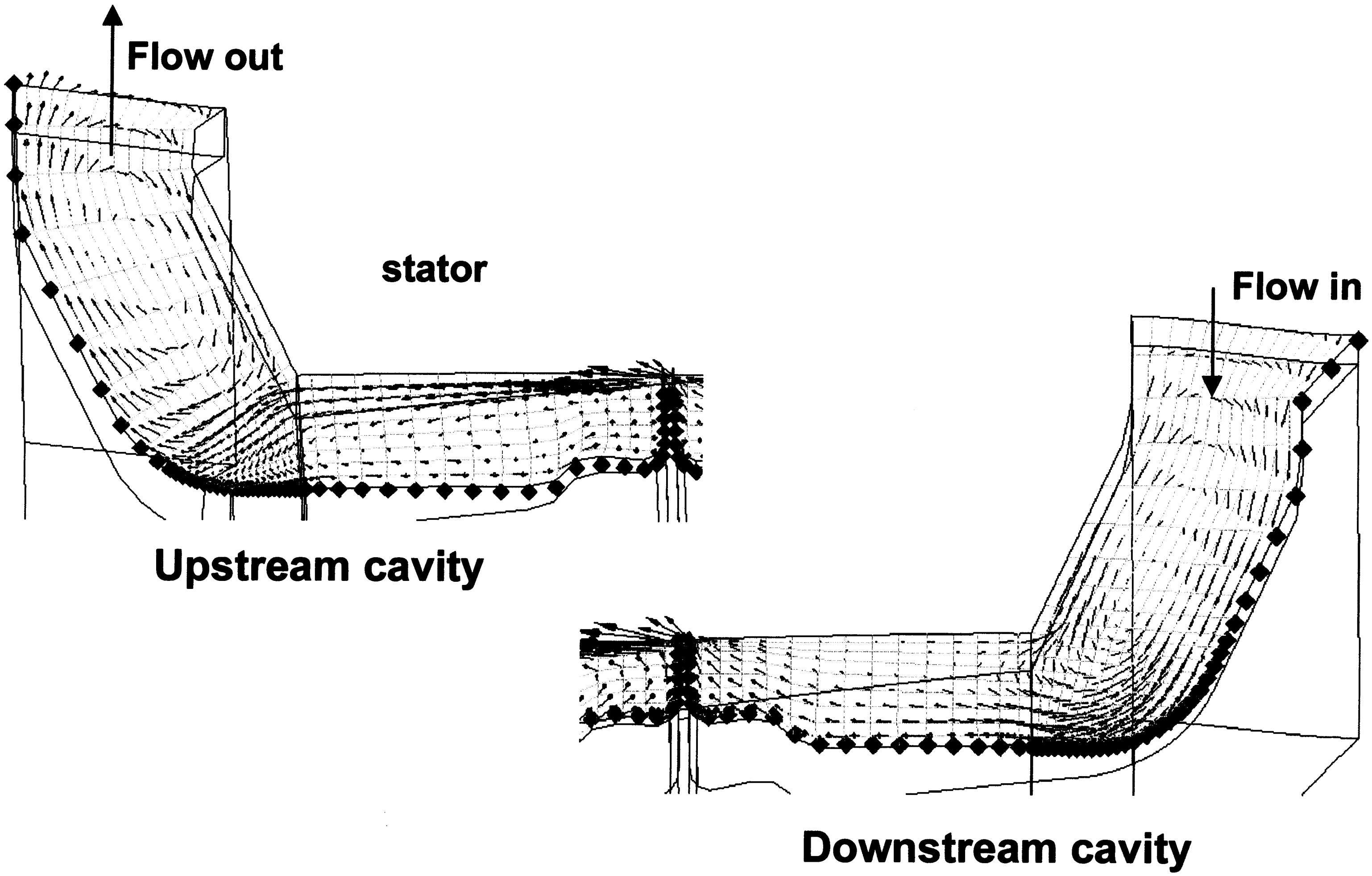
- Representative Vector Plots in the Cavity Shown and Compared with Sample Data

- Calculated Leakage Rates ~ 0.045% as against 0.05%, estimated at $\phi = 0.4$

P-4117-11/31

LSAC RIG

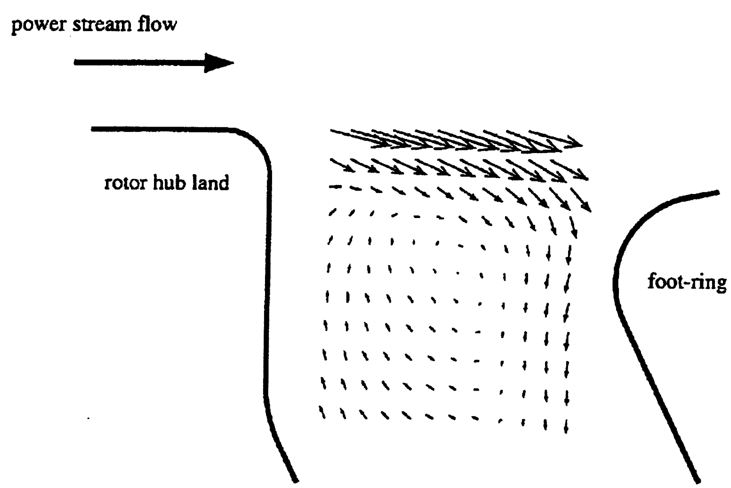
Cavity Vector Plots, Plane Under Stator Blade



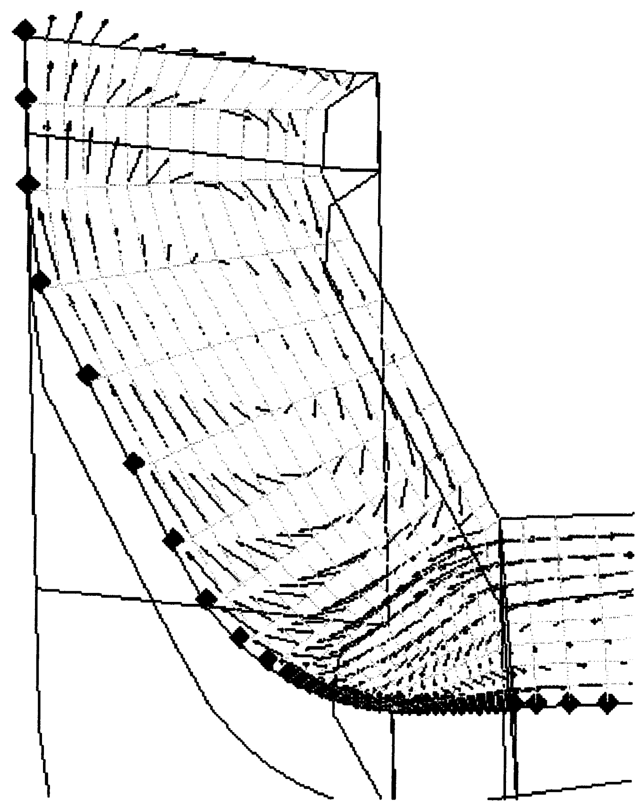
P-4117-11/32

LSAC RIG

Vector Plot in Upstream Rim Seal Under Stator Blade (Qualitative Agreement)



Experiment



Computed

P-4117-11/33

REMARKS ON SIMULATION PROCEDURE

- Steady State Solution for SCISEAL and Startup Solution for TURBO Without Interfacing as Initial Condition is a Must

- Maximum CFL Numbers in TURBO were Kept about 10-12 for Stability

- Different Number of Subiterations in the Two Codes Needed per Data Exchange
  - allow the solutions to settle after each exchange
  - 25-40 for SCISEAL, 3-5 for TURBO

- Time for Execution was Long as Expected; Testing to see if Higher Stable CFL can be used with Current Number of Subiterations

P-4117-11/34

SUMMARY

- Interaction between Mainpath and Secondary Flow Important; Need Details of Transient, Detailed Flow Information for Performance Prediction and Designs

- Numerical Methodology for Coupled, Transient Simulations Developed
  - validated codes: SCISEAL and MS-TURBO for secondary and primary flows
  - interfacing algorithm to link data at interface

- Validated Using a Checkout Case; by Comparing Coupled Code Solutions with Single-Code (SCISEAL Solutions)

P-4117-11/35

SUMMARY (CONTINUED)

- Flow in H.P. Rig Simulated at 2 Cavity Inlet Pressures
  - 2-D, steady-state, axisymmetric and 3-D transient, coupled solutions obtained, reasonable agreement of leakage flows
  - variations in rim seal seen at different θ locations
  - ingestion predicted at the lower cavity inlet pressure as seen in experiments

- LSAC Simulations in Progress
  - representative cavity vector plots
  - in qualitative agreement with experiments

- Additional Validation Cases being Sought from WPAFB
  - compressor and/or turbine sections

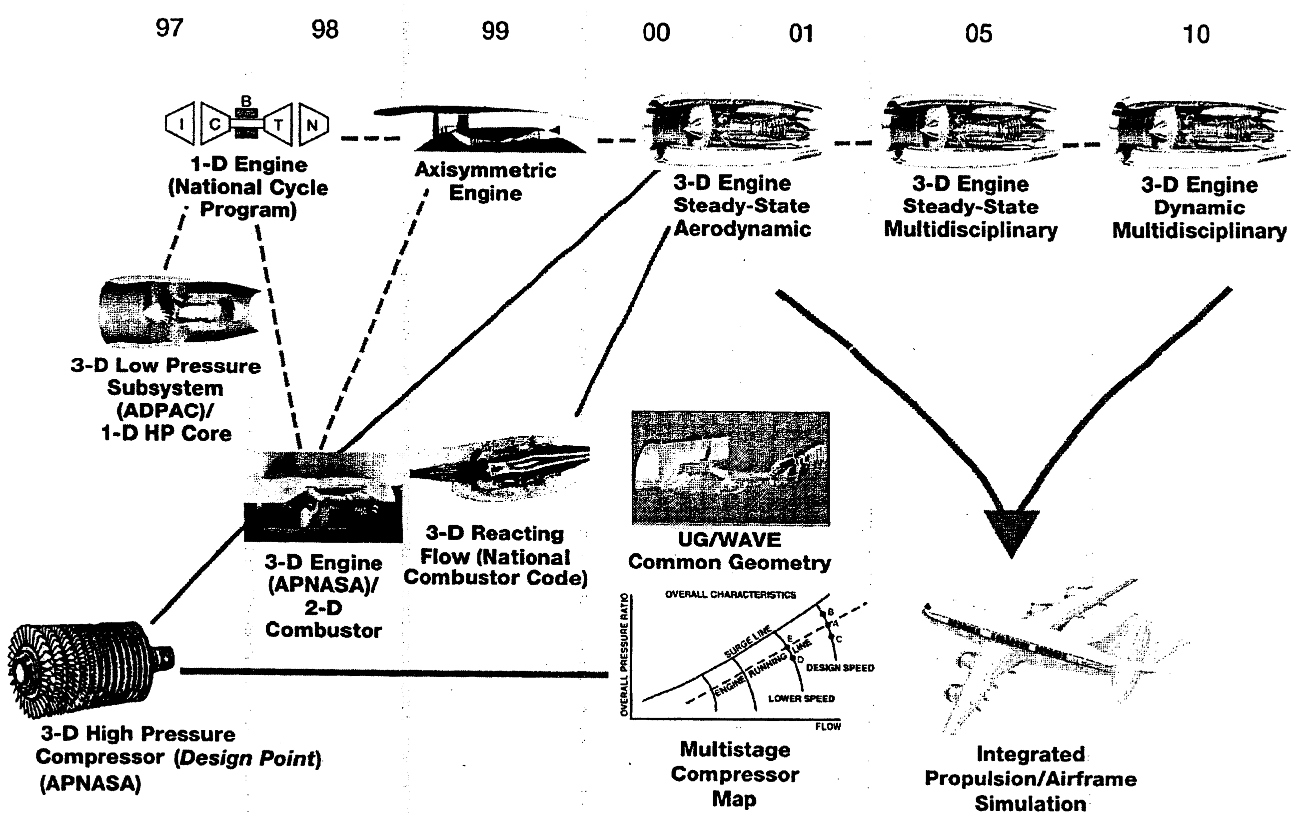
- Future Plans
  - improve post-processing
  - β-release to NASA, OEM
  - continue validation simulations, H.P. Rig data, LSAC, WPAFB data

P-4117-11/36

NPSS ENGINE SYSTEMS SIMULATIONS

Joseph P. Veres
NASA Glenn Research Center
Cleveland, Ohio

Roadmap for NPSS Overnight Simulations



Multidisciplinary Design Optimization Using UG/WAVE

Objective

To develop an associative control framework in a Unigraphics CAD environment enabling multidisciplinary design of propulsion systems

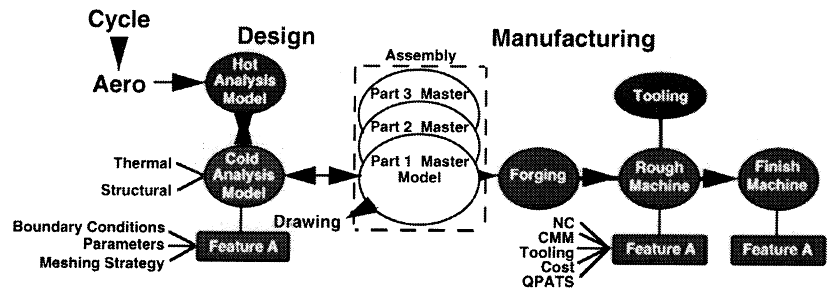
Approach

To apply WAVE (What-if Alternative Valve Engineering) CAD design tool to control key design variables to create a complete gas turbine engine in a Unigraphics environment

Benefits

- The creation of a common geometry will encourage level concurrent engineering
- Supports concept to detailed design engineering and rapid optimization
- Standardization and automation of design practice and serves to capture the "corporate memory"
- Contract with GEAE NAS3-98004 Task Order #2

Common Geometry



Point of Contact

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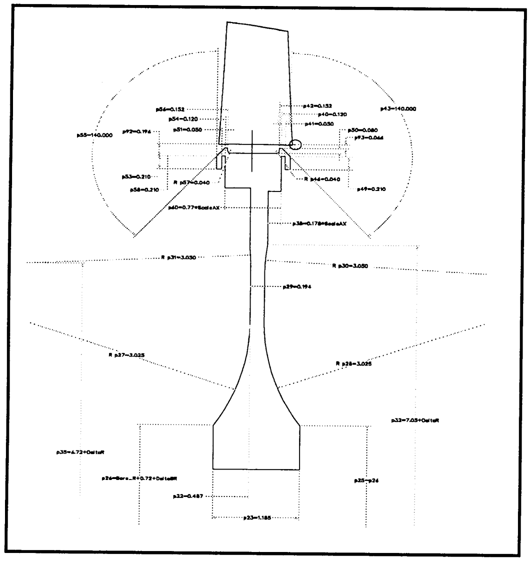
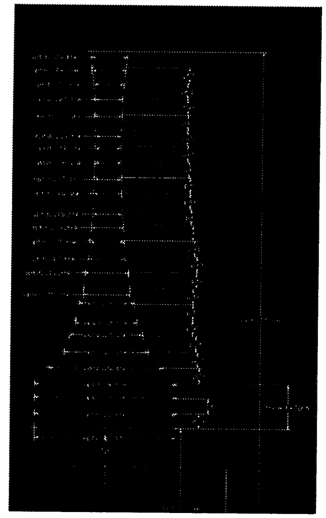
Multidisciplinary Design Optimization Using UG / WAVE

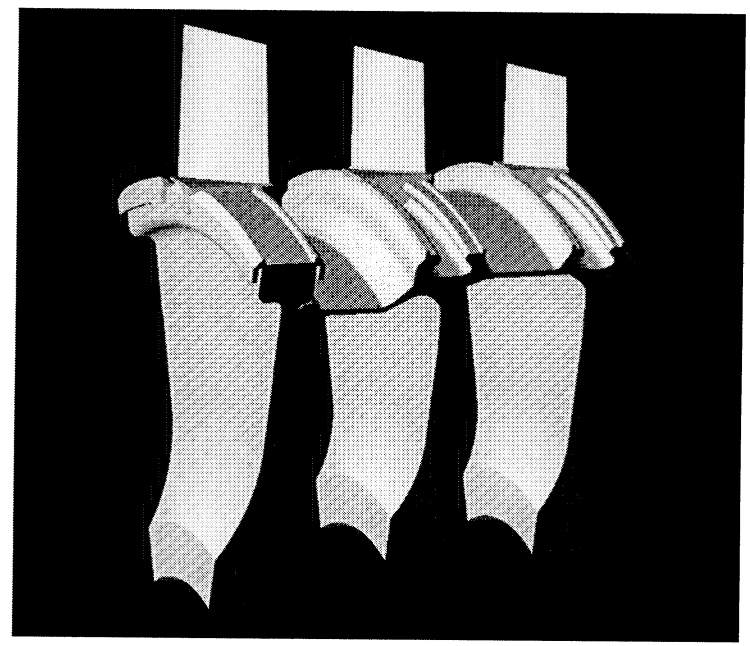
Design Rules Drive Knowledge based Unigraphics (UG) Sketch

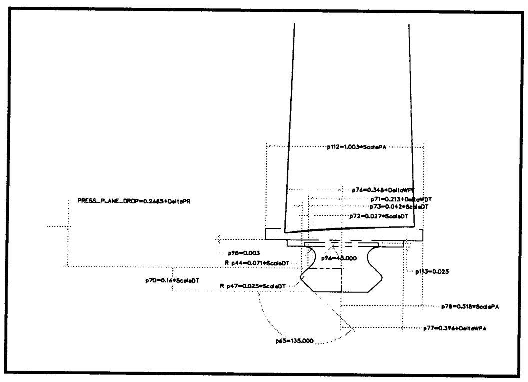


Disk 2D Profile, Calculated Blade and Post Loads

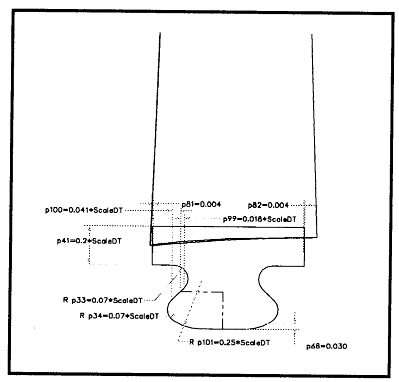


UG solid modeling feature is used to unite the base curves into one solid associative geometry of a complex object



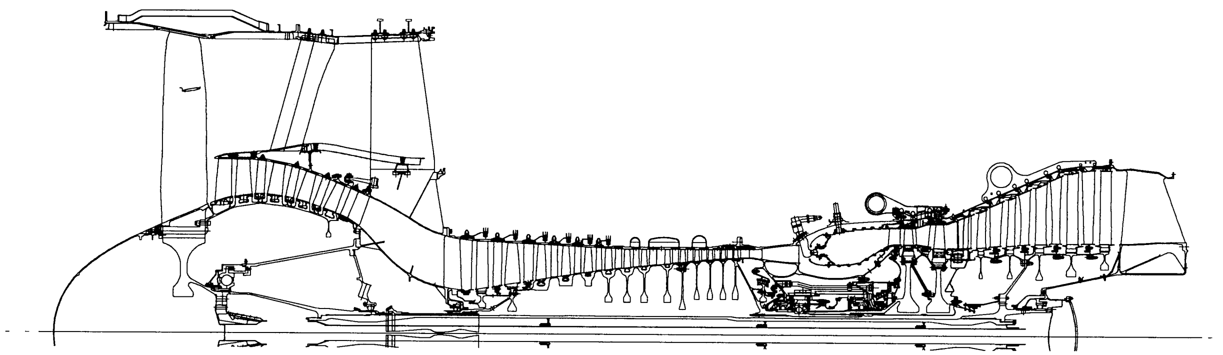


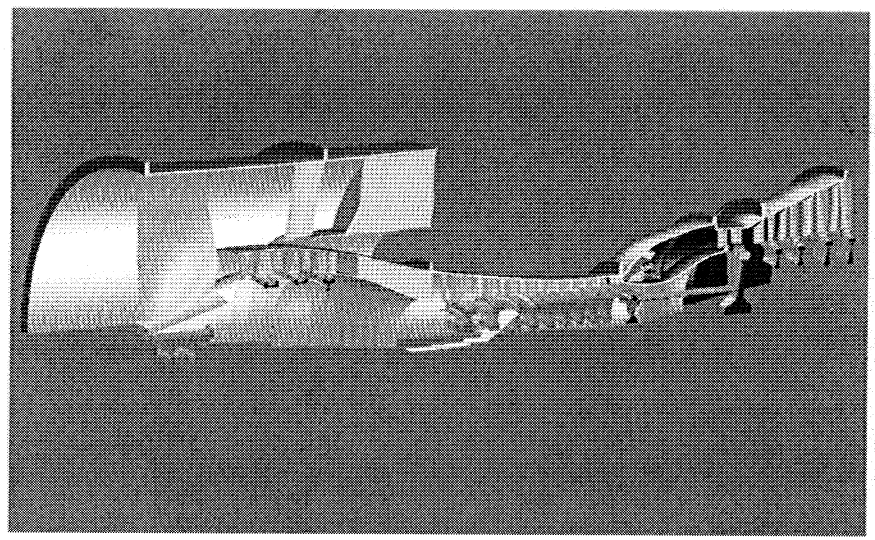
Disk Slot Sketch



Blade Dovetail

Multidisciplinary Design Optimization Using UG / WAVE





- High-fidelity rapid creation of detailed geometry for system level concurrent engineering
- Controlled automation of design changes
- Links technical requirements with the creation of the base geometry at all levels
- Supports concept to detailed engineering
- Captures corporate knowledge

Flow Solver for National Combustion Code

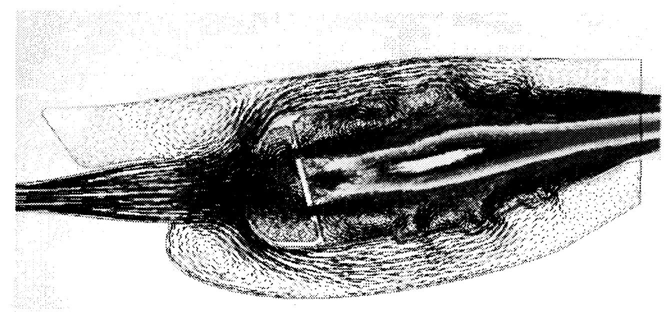
Multidisciplinary Combustor Design and Analysis System with Emissions Modeling

Objective

Develop an integrated system of codes for combustor design and analysis to enable a factor of 5 reduction in cost and analysis time

Approach

- ✦ Develop a computational combustion dynamics capability (CCD)
- ✦ CORSAIR-CCD is a Navier-Stokes flow solver based on an explicit four-stage Runge-Kutta scheme
- ✦ Unstructured meshes
- ✦ Run on networked workstation clusters
- ✦ The solver can be linked to any CAD system via the Patran file system
- ✦ Contract with Pratt & Whitney NAS3-26618 Task Order #62
- ✦ Contract with CFD Research Corp. NAS3-97118



Significance/Metrics

- ✦ The National Combustor Code is a system of codes that will enable the multidisciplinary analysis of the full combustor from compressor exit to turbine inlet
- ✦ The CORSAIR-CCD code is the baseline flow solver module

Point of Contact

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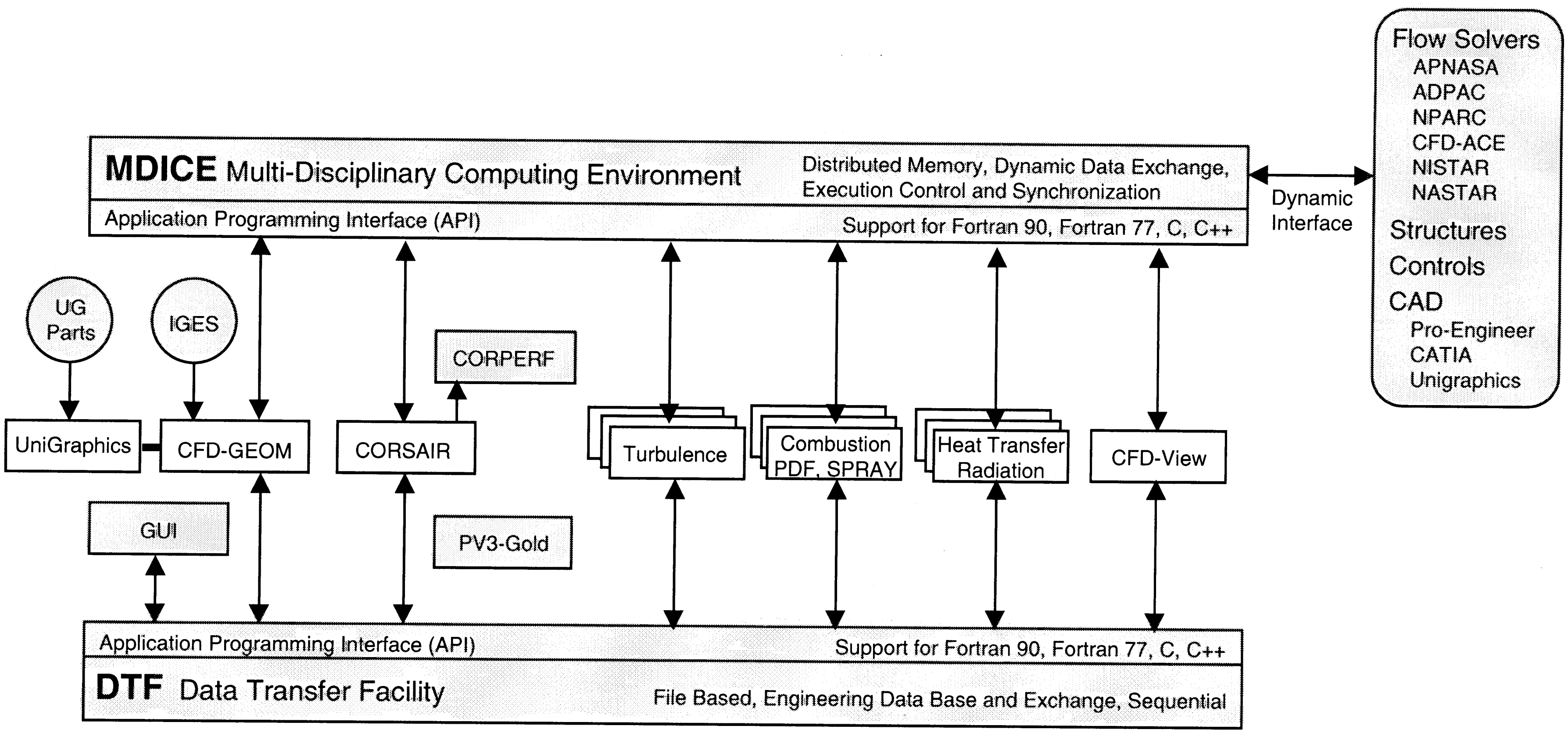
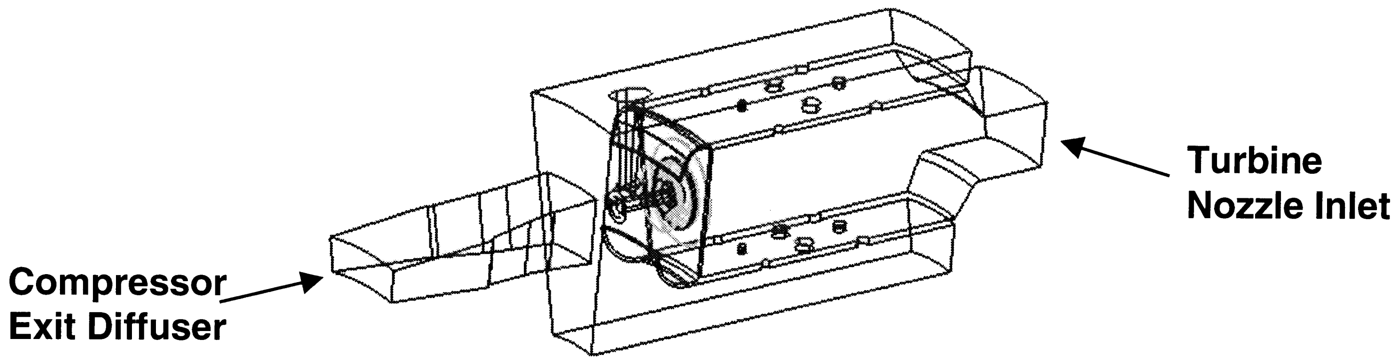
National Combustion Code Computing Framework

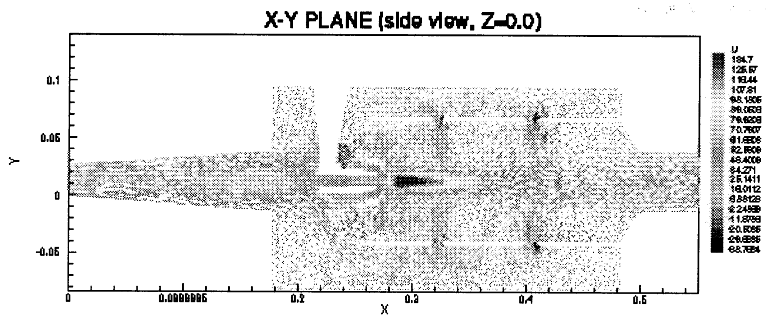
Conceptual Overview



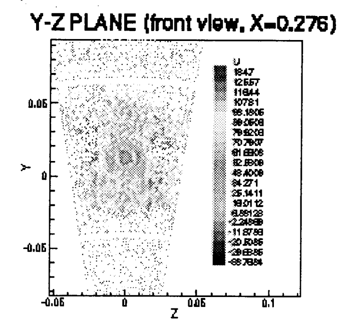
National Combustion Code



Full Combustor Geometry Outline



Flow Simulation
(Absolute Velocities, Meridional View)



Flow Simulation
(Absolute Velocities, Axial View)

Low Pressure Subsystem 3-D Model

Objective

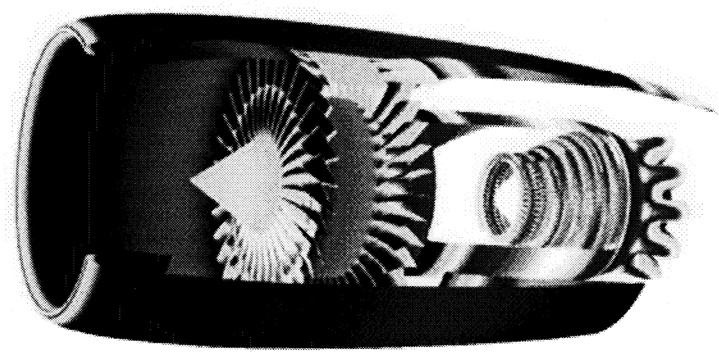
Develop a detailed flow simulation of the low pressure subsystem within a gas turbine engine using a simplified core engine model.

Approach

- Apply the ADPAC 3-D Navier-Stokes flow code to the Energy Efficient Engine LP Subsystem consisting of: nacelle, inlet, fan, bypass duct, mixer, LP turbine and nozzle creating a 3-D flow model of LP Subsystem
- BC's at the core engine inlet and exit will be specified from thermodynamic cycle and data
- The simulation runs on parallel on distributed workstations
- Contract with Allison NAS3-27394 Task Orders #13, #17

Impact/Metrics

- Evaluate the interaction effects between the LP subsystem components while considering the boundary conditions at the core engine
- The LPS model will reduce design/development time by enabling the designer to numerically investigate engine operability



Applications

- HSR High Speed Civil Transport engine
- AST engines to assist in the development and certification of growth versions of existing engines
- Allison AE 3007 Engine

Point of Contact

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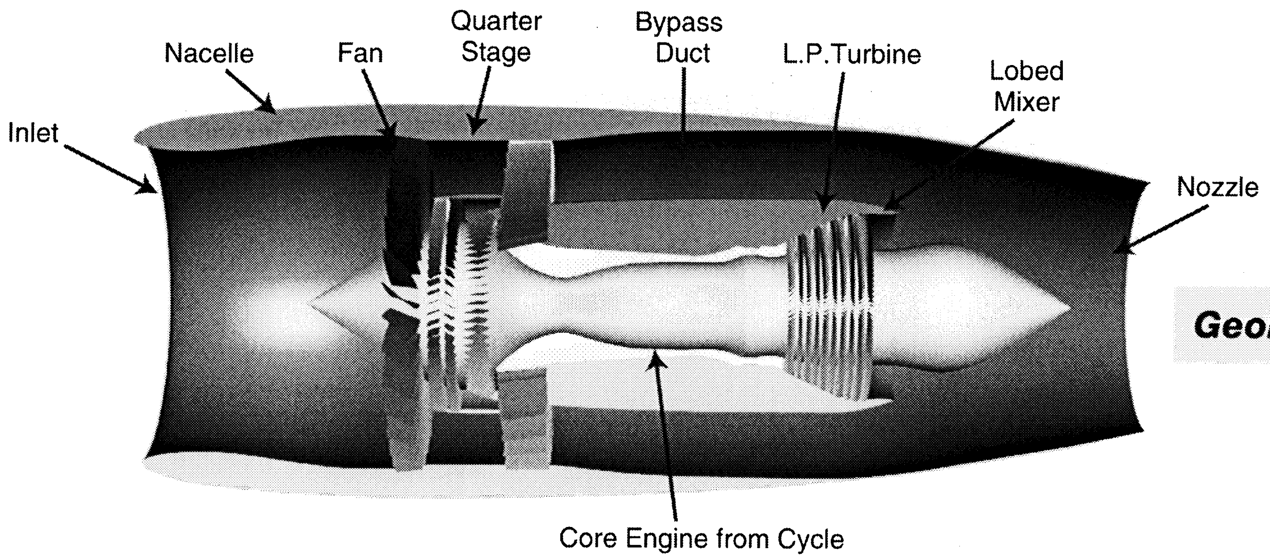
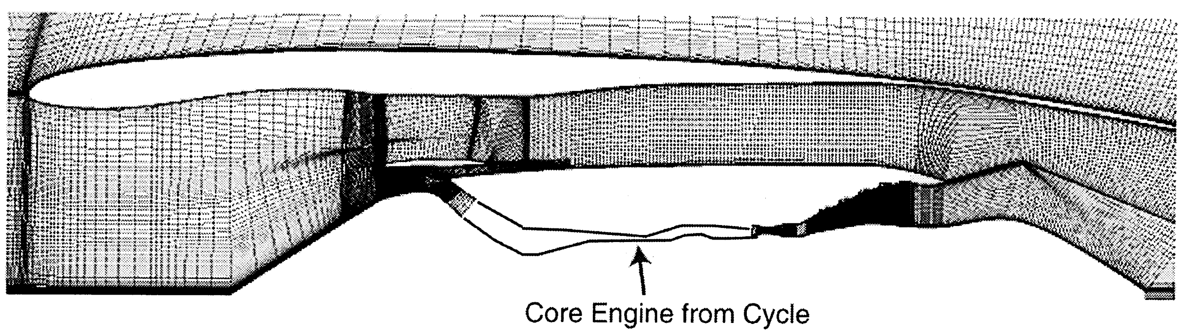
Flow Simulation of the EEE Gas Turbine Low Pressure Subsystem

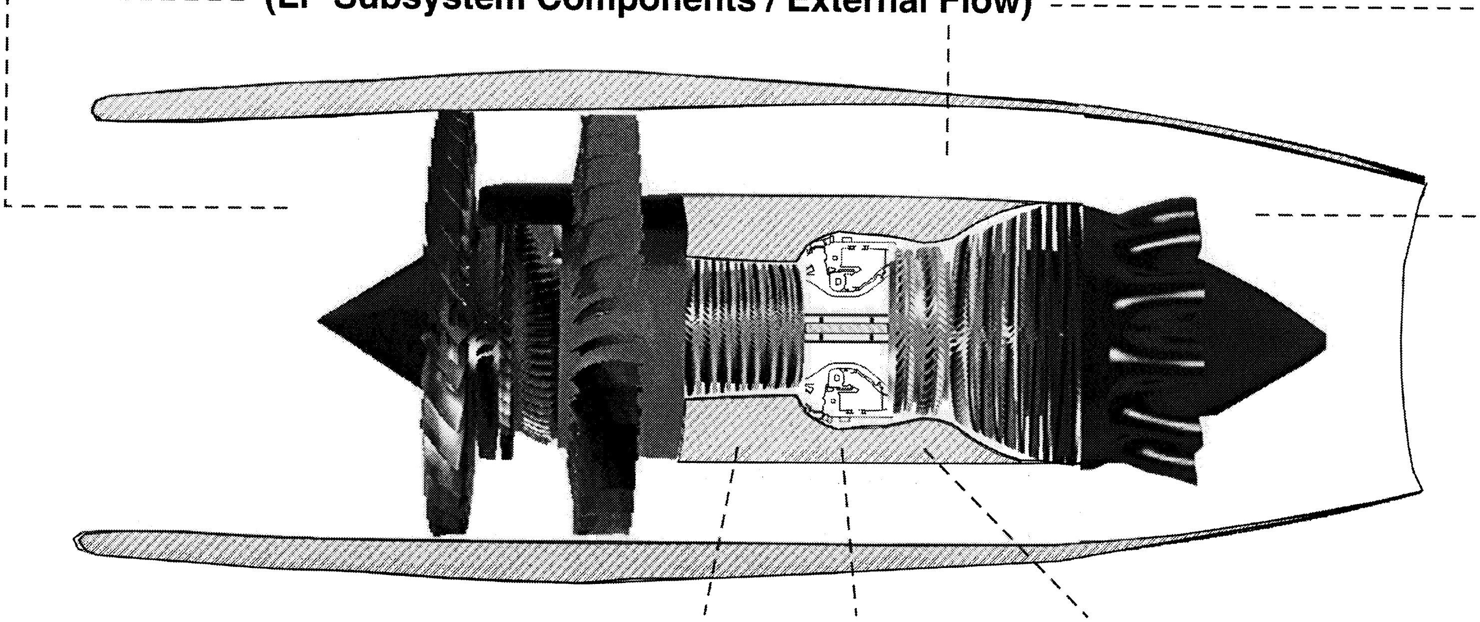


Geometry



Grid

Flow Simulation of the EEE Gas Turbine Low Pressure Subsystem

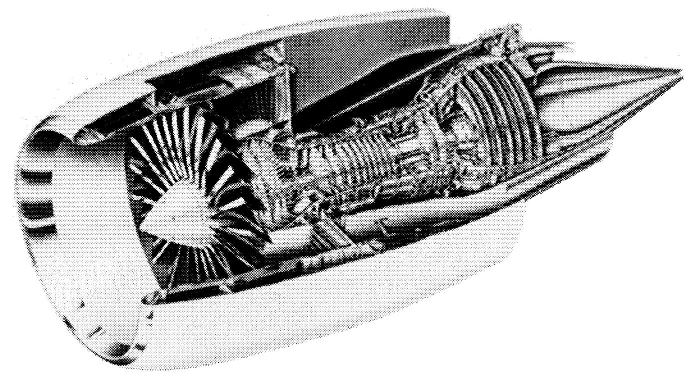


Energy Efficient Engine featuring Dual Spool Concentric Shaft Arrangement. Computer model of the Low Pressure Subsystem (spool) is with the ADPAC code, while the High Pressure (core engine) model is simulated with the NEPP/NCP thermodynamic cycle code.

HPCCP/NPSS Plan Detailed Flow Simulation of Modern Turbofan Engine

Objective

Develop a detailed flow model of a full turbofan engine that runs on parallel workstation clusters overnight. The model will simulate the flow in the primary flowpath andwill have a simplified combustor model.



Approach

- ✦ The 3-D flow analysis models the GE90 turbofan engine using APNASA (NASA's average passage flow code)
- ✦ The project leverages from current efforts between NASA and G.E. in developing the APNASA flow code and workstation clustering technology
- ✦ Contract with GEAE, NAS3-26617, Task Order #65

Significance/Metrics

The overnight 3-D flow simulation capability of the primary flowpath in a complete engine will enable significant reduction in the design and development time of gas turbine engines.

Point of Contact

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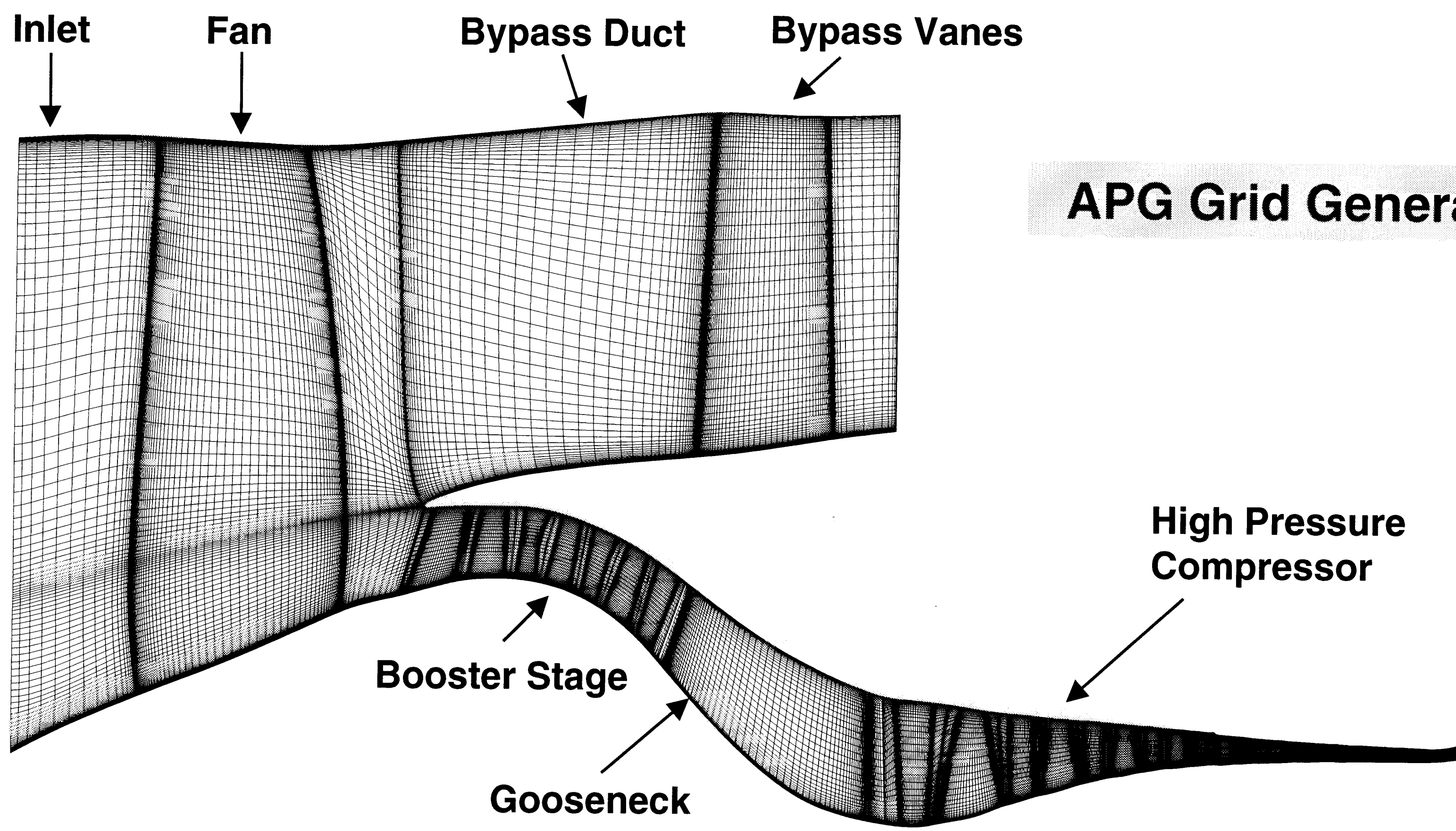
Detailed Flow Simulation of Modern Turbofan Engine

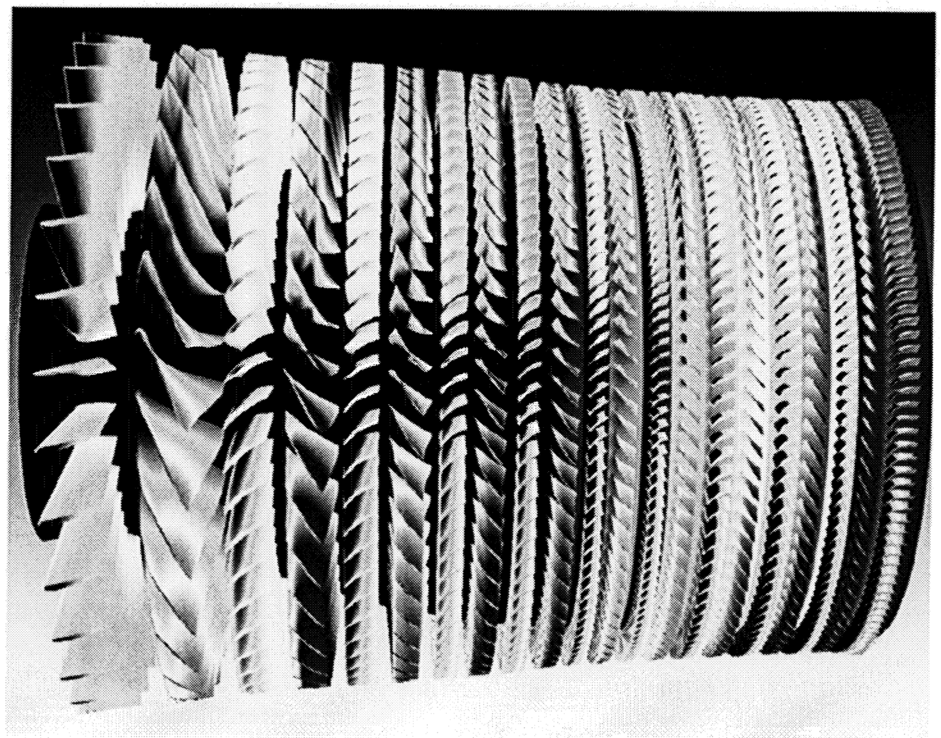


APG Grid Generator

Grid Generator for full GE90 compression system including fan, booster stage, high pressure compressor and bypass vanes

1998
NPSS Industry Review

Detailed Flow Simulation of Modern Turbofan Engine



APNASA multi-stage flow simulation of complete GE90 high pressure compressor, with excellent comparison between flow model and rig test data. Grid generation with APG, developed at NASA Lewis, and visualization is with APVIZ, developed at MIT. The simulation exploits two levels of parallelism with extremely high parallel efficiency.

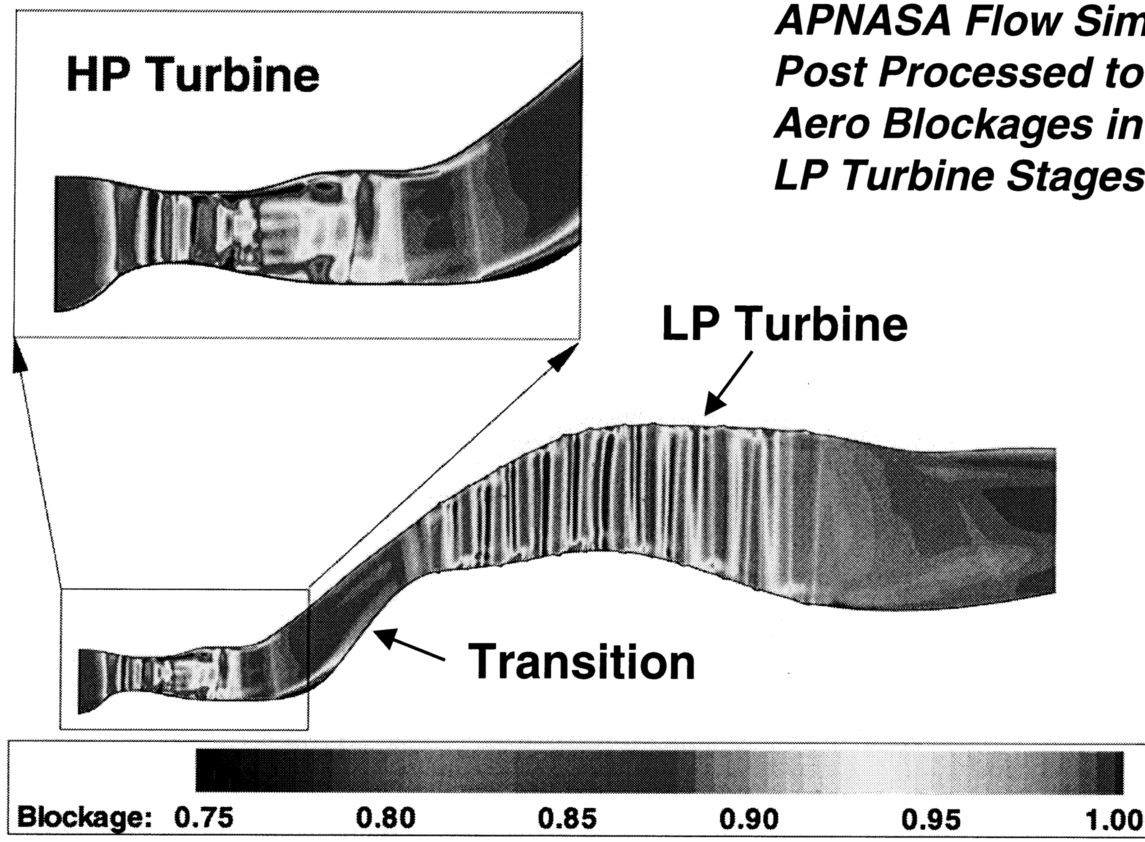
Detailed Flow Simulation of Modern Turbofan Engine

Engine Turbine Relative Mach Numbers

- Full HP and LP turbine coupled simulation with APNASA
- Cooling air included through source terms
- Leakage through seals and around blade and vane seals was modeled

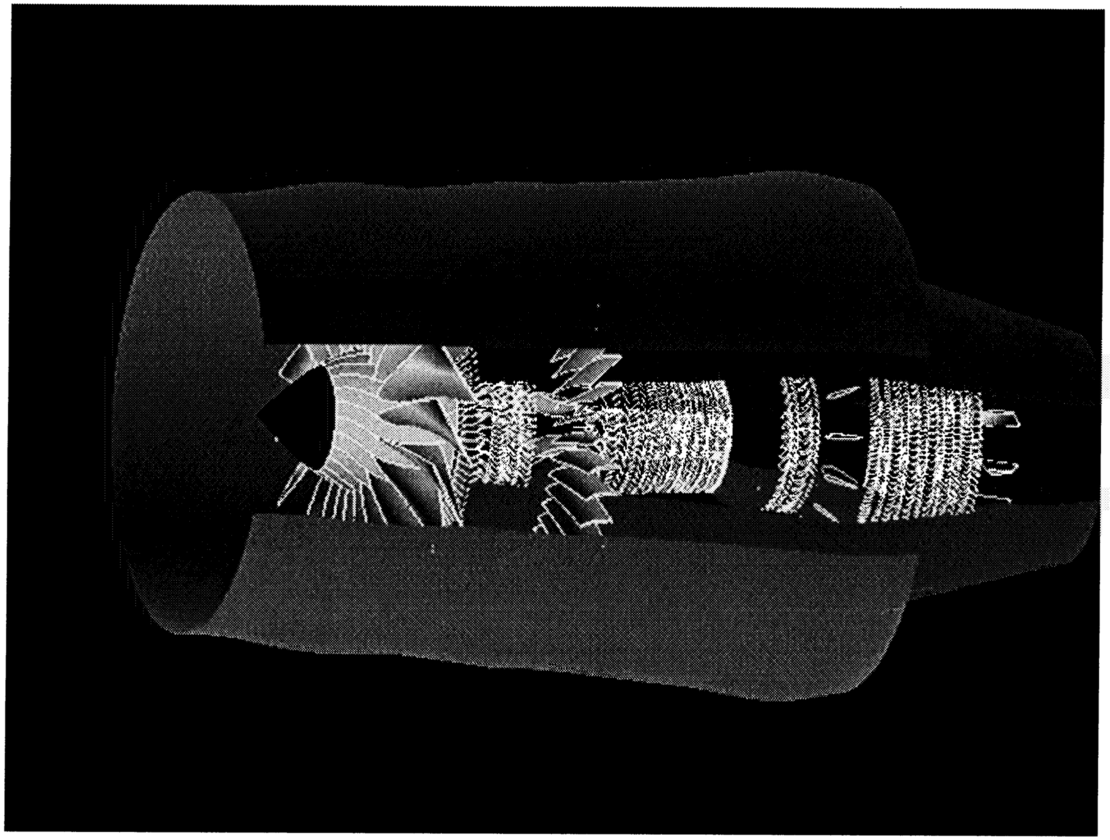
Detailed Flow Simulation of Modern Turbofan Engine

APNASA Flow Simulation Post Processed to Show Aero Blockages in HP and LP Turbine Stages



APNASA simulation of coupled high pressure and low pressure turbines of GE90 engine

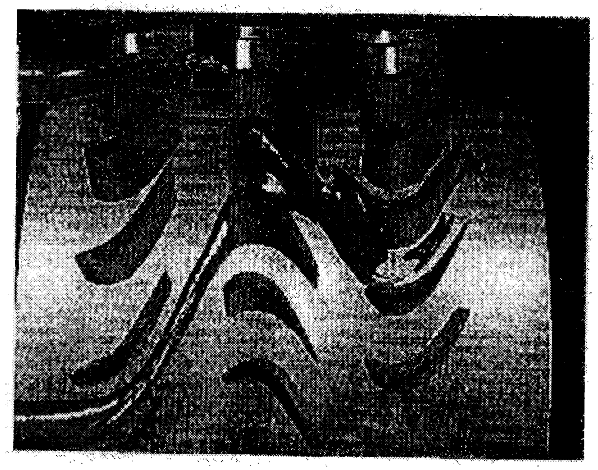
Detailed Flow Simulation of Modern Turbofan Engine



- Full engine simulation visualization with FEVis
- Uses pV3 library from Bob Haimes (MIT)
- Optional MPEG output for animation

Navier-Stokes flow simulation of the GE90 engine primary flowpath using the APNASA average-passage code. Complete compression system and turbines were modeled as single simulations.

Turbine Blade Tip and Outer Air Seal



Objective

- Improve computer models for high pressure turbine rotor tip & outer air seal (OAS) heat loads using CFD as a close coupled tool.
- Use deterministic stresses to model the unsteady heat loads with steady CFD simulation

Approach

- Contract with UTRC NAS3-26618, Task Order #28
- Unsteady analysis required to pass full burner pattern information to the rotor
- Establish unsteady numerical data base for multiple inlet temperature profiles from burner
- Apply 2D and 3D deterministic stresses from unsteady Euler to steady Navier-Stokes simulation

Significance / Metrics

- Current steady CFD fails to capture hot gas distribution in rotor
- Inexpensive CFD analysis of full burner pattern effects on turbine rotor
- Hot streak migration through turbine blades can be simulated with steady flow code using deterministic stress data base

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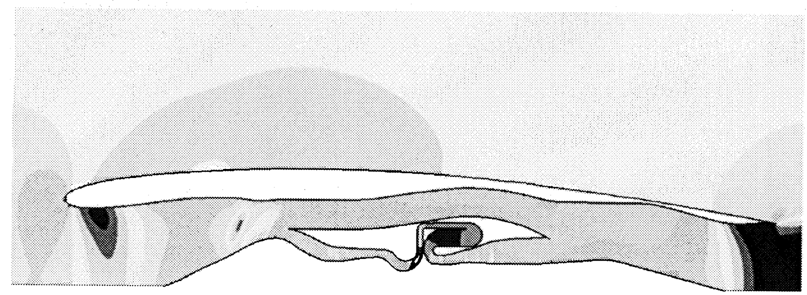
CD-97-75945

ENG20 Simulation of Turbofan Engine



Objective

Develop a US industry standard for an axisymmetric flow simulation environment of a full gas turbine engine. The model will computationally evaluate the interactions between components.

Approach

To evaluate the capabilities of the ENG20 code using a test case (AlliedSignal 731-60 engine)

- Link AE's compressor and turbine axisymmetric streamline curvature codes UD0300M and TAPS with ENG20, to provide boundary conditions
- Evaluate GE's Global Data System, and convergence time
- Provide to NASA the developed interfaces which link the component codes to ENG20
- Contract with AlliedSignal Engine Co. NAS3-27483, Task Order #14

Significance/Metric

The high fidelity full engine simulation can reduce the number of design and test iterations in an engine development program and lower acquisition cost

Point of Contact

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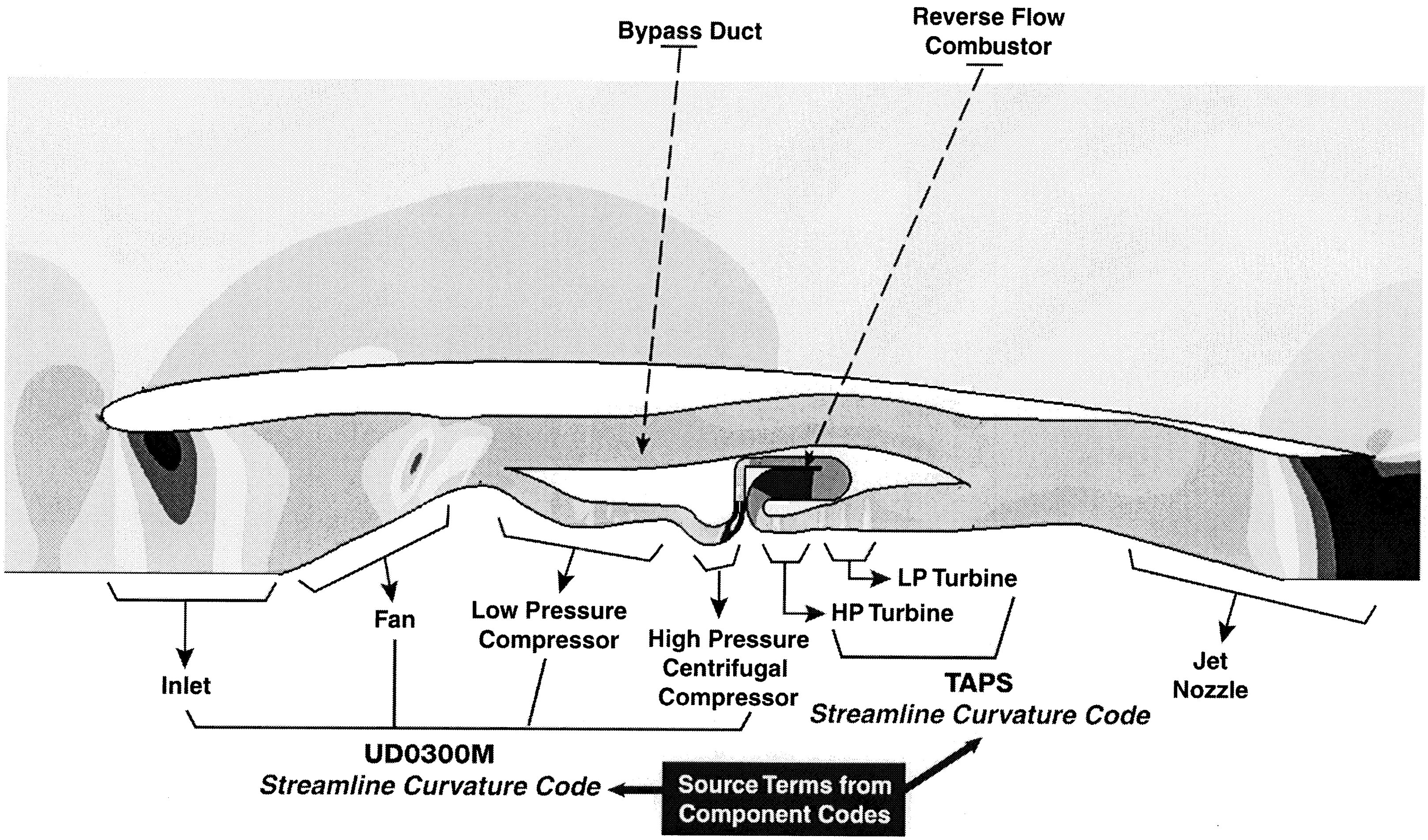
ENG20 Simulation of AlliedSignal 731-60 Gas Turbine Engine

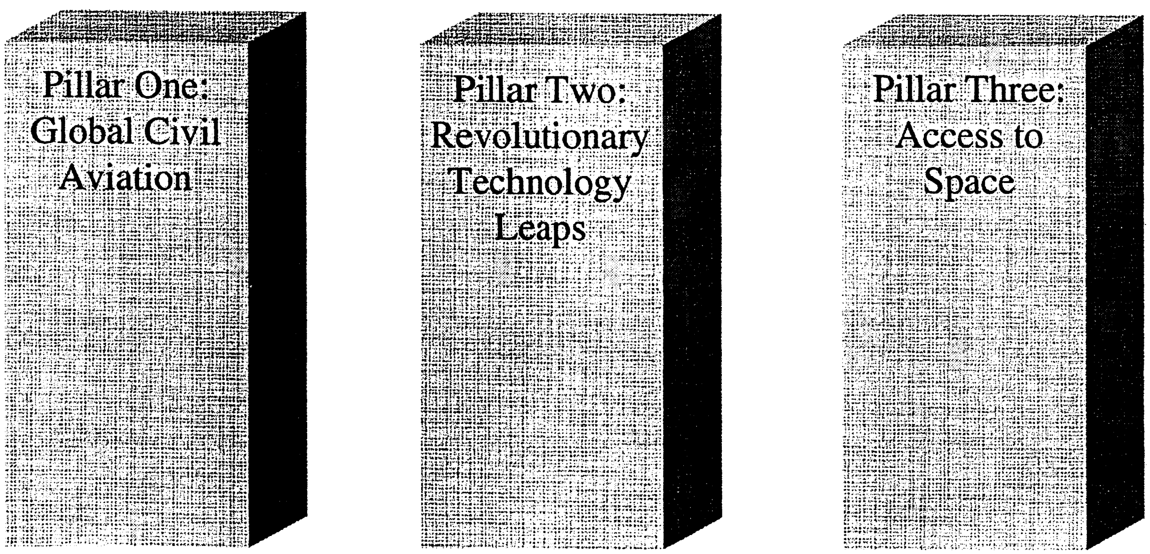


THE TRAILBLAZER PROGRAM

Charles J. Trefney
NASA Glenn Research Center
Cleveland, Ohio

"Three Pillars for Success"

Established in 1997 by the
Office of Aeronautics and Space Transportation Technology (OASTT)
NASA Headquarters, Washington D.C.



http://www.hq.nasa.gov/office/aero/

Pillar Three: "Access to Space"

The Challenge

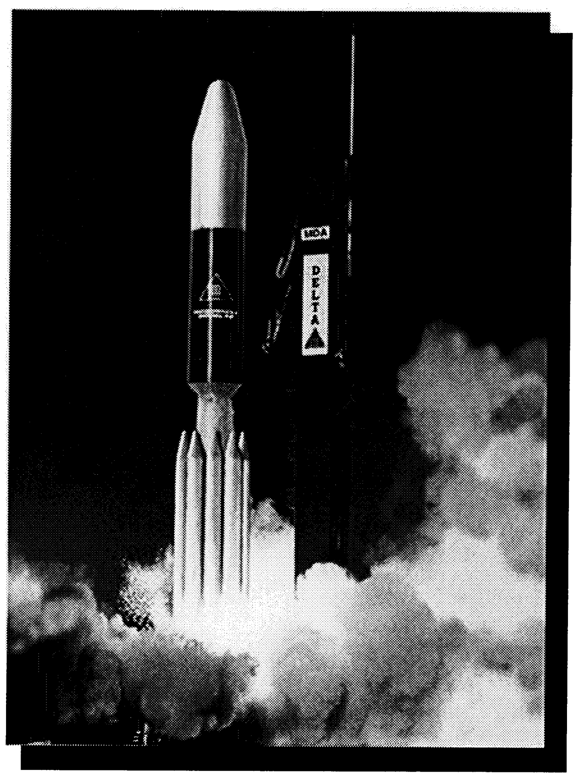
"Without affordable and reliable access to space, the future of the space program is hindered by the high cost, low reliability, and poor operability of payload launch..."

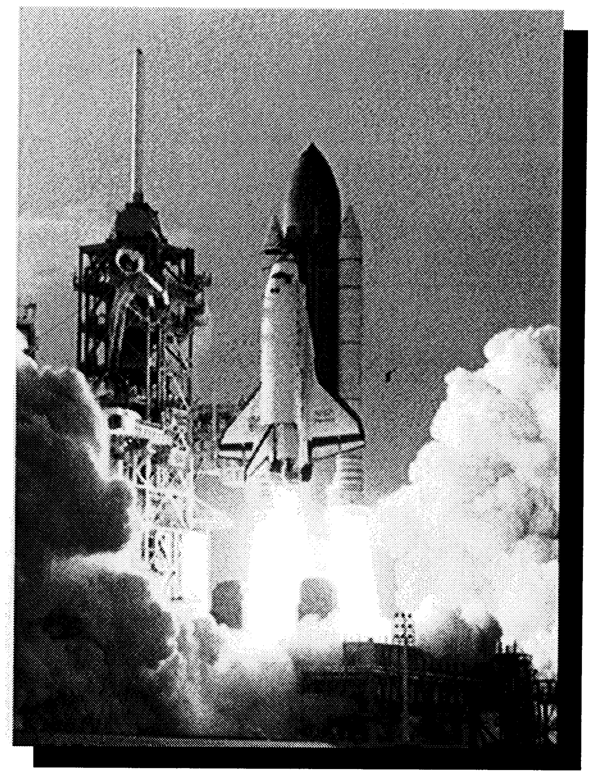
"The cost of space access is roughly $10,000 per pound of payload delivered to low-Earth orbit."

http://www.hq.nasa.gov/office/aero/

Why is Space Access So Costly?

- Expendable components
- Expendable vehicles
- Vehicle re-assembly
- Refurbishment
- Supply and demand

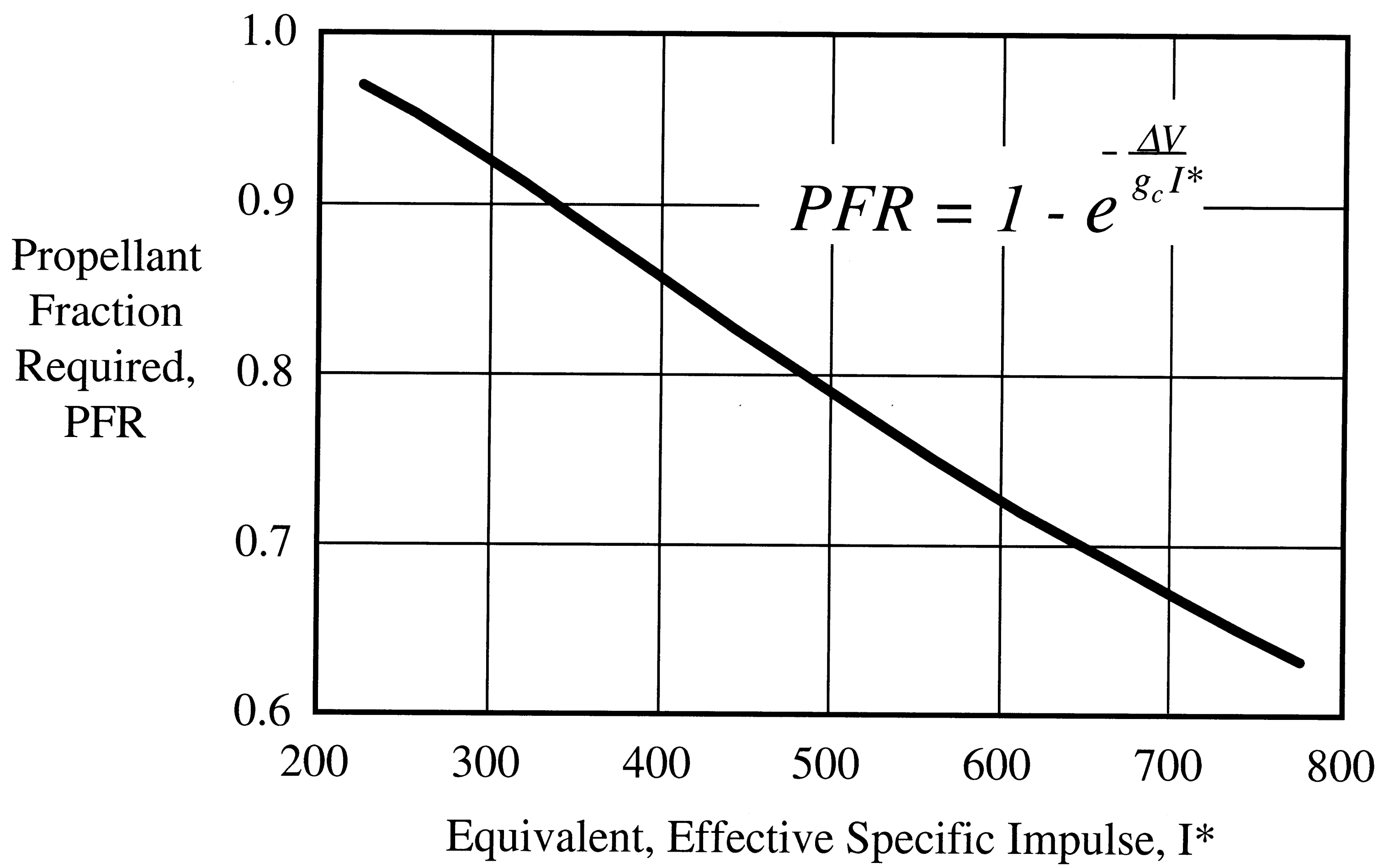




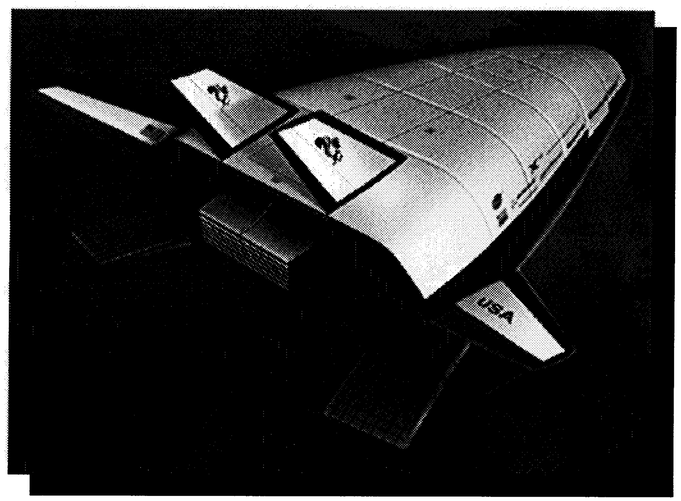
A highly-reusable, single-stage-to-orbit (SSTO) launch vehicle would dramatically reduce the cost of space access...

The "Rocket Equation" for SSTO

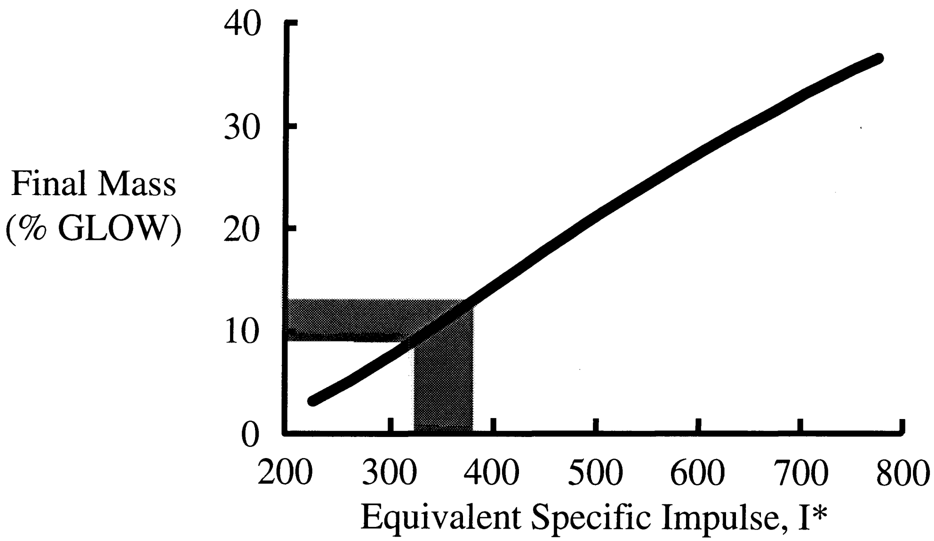
The amount of propellant required to achieve orbit is governed by Newton's second law...

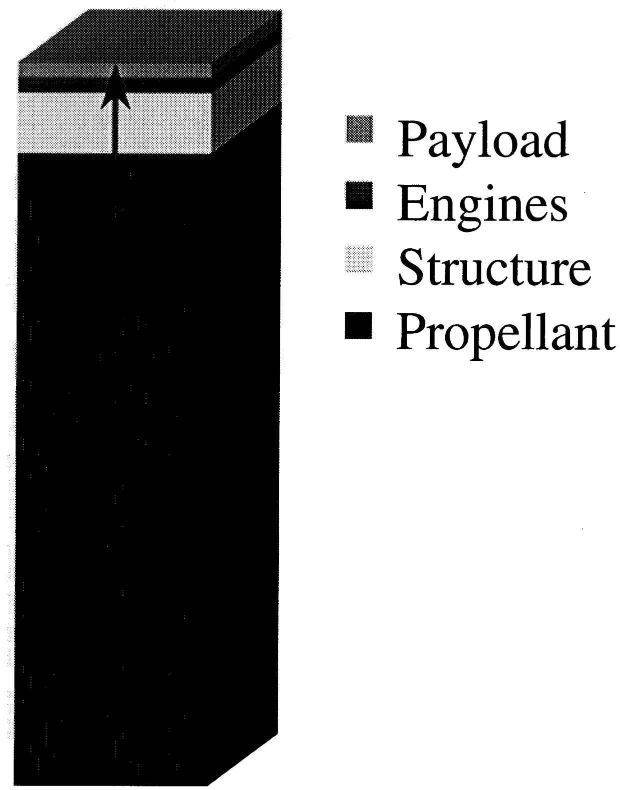


The Rocket I* "Barrier"



Rockets are limited to I values below 400, leaving only 10-12% of the gross lift-off weight for reusable structure and engines*

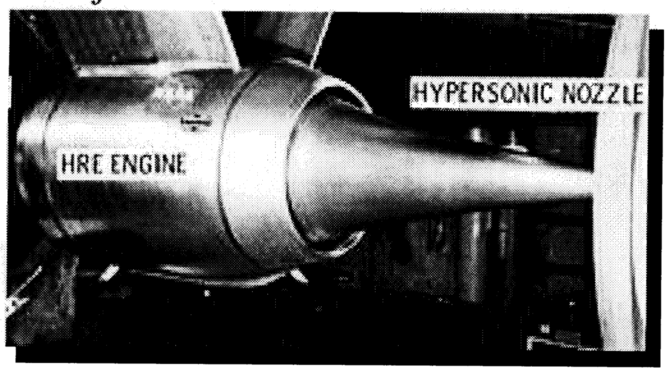




Rocket-Based Combined-Cycle Engine

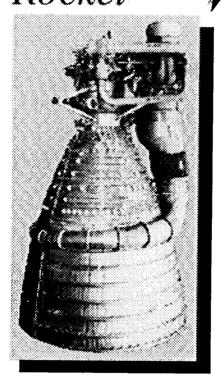
RBCC engines combine the desirable features of the rocket and ramjet cycles in a single, highly-integrated propulsion system

Ramjet



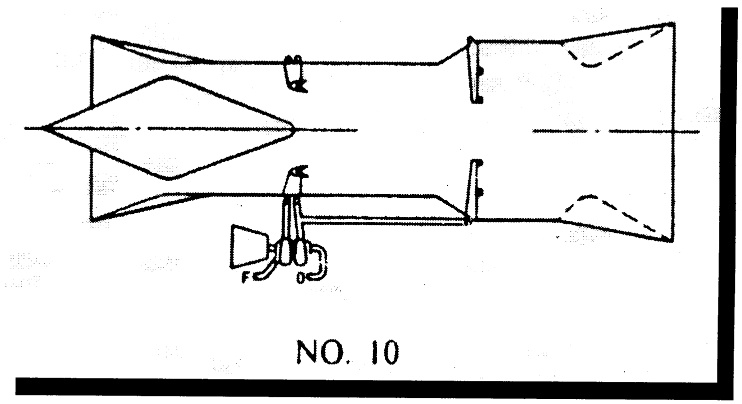
- *High efficiency at supersonic speed*
- *Cannot generate static thrust*
- *Low thrust-to-weight ratio*
- *Requires atmospheric oxygen*
- *Uncertain hypersonic performance*

Rocket



- *Thrust at any speed*
- *Light weight*
- *Low efficiency*

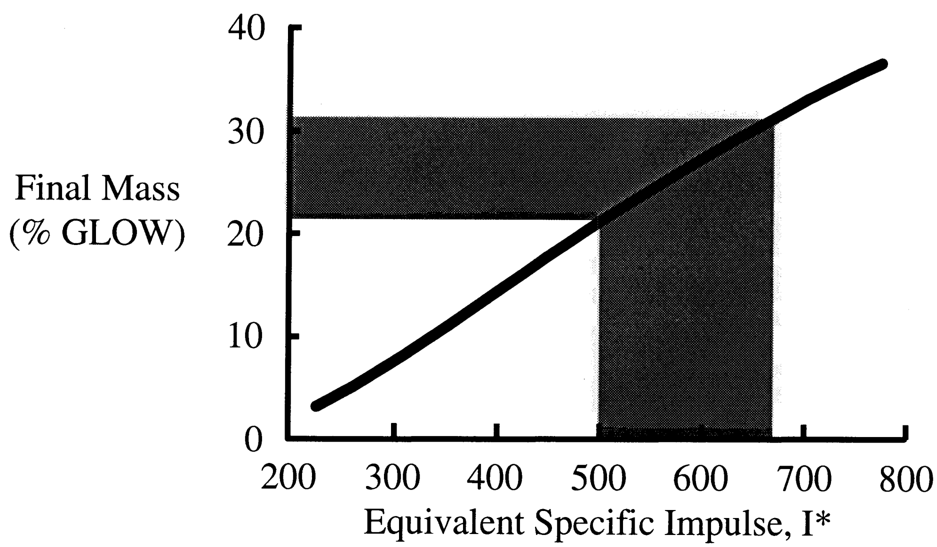
Rocket-Based Combined-Cycle (Escher, Circa 1966)

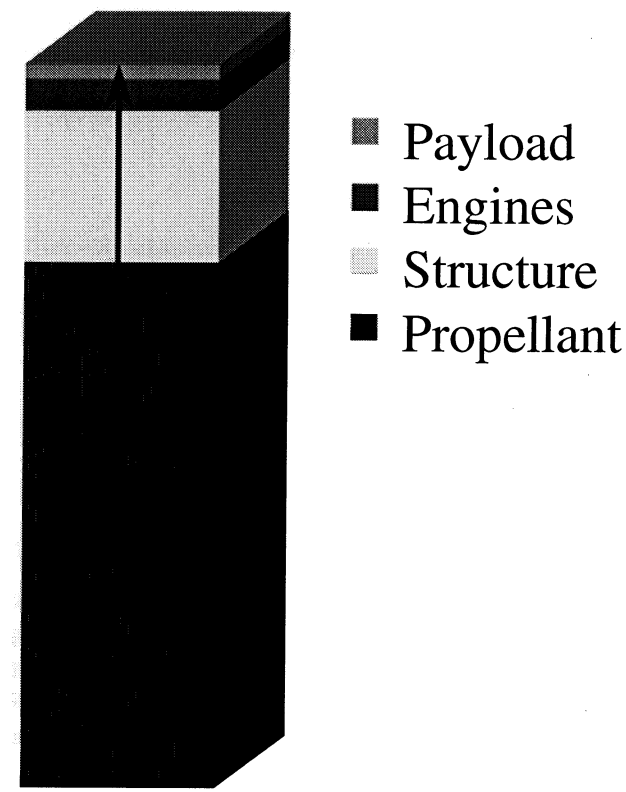


- *High thrust at lift-off*
- *High overall efficiency*
- *Operates from lift-off to orbit*

Potential for Reusability

RBCC propulsion provides the potential for reusable SSTO by reducing the fraction of propellant required

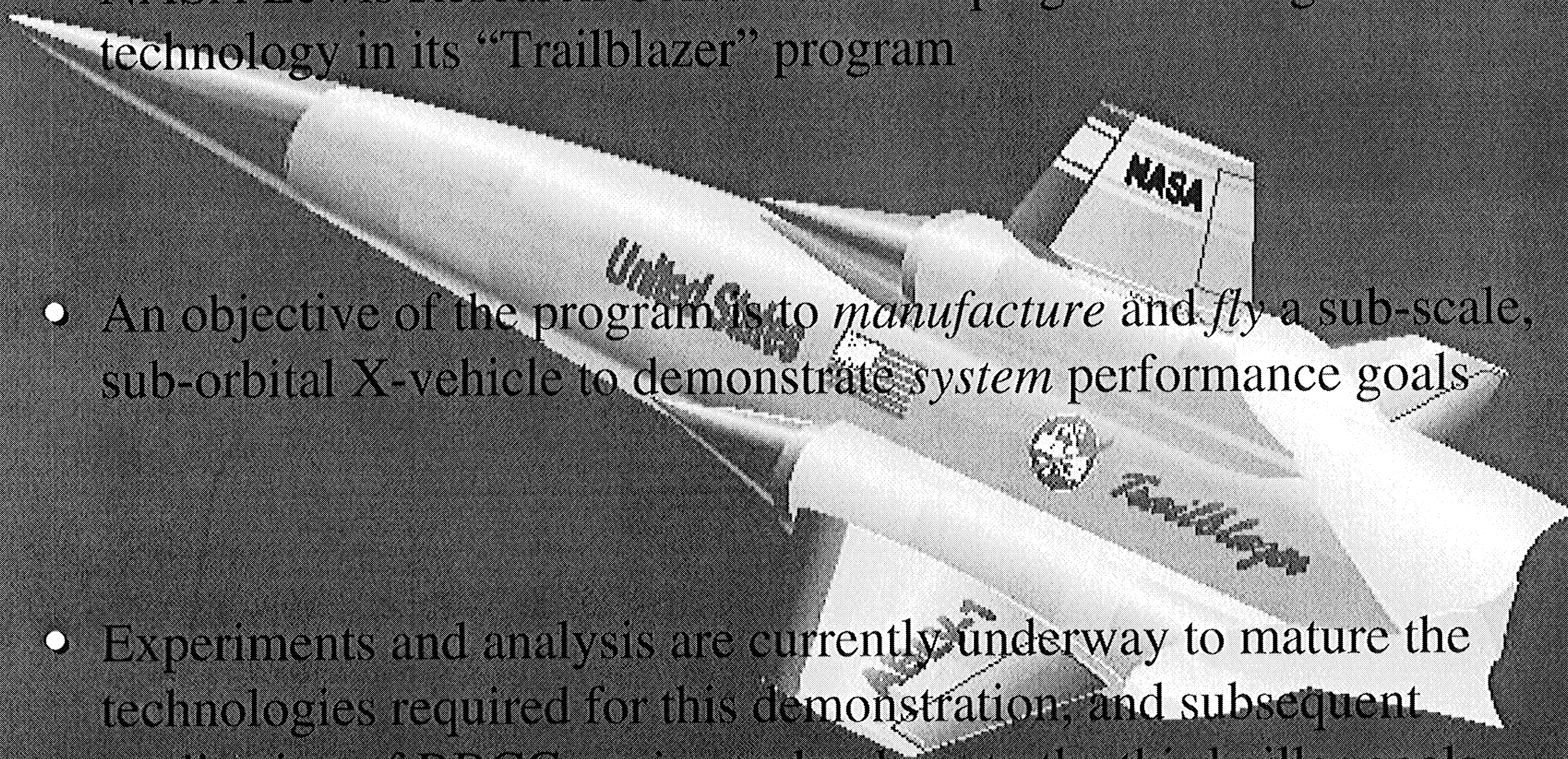




Factors Mitigating RBCC Performance

- Weight and complexity of added propulsion components
- Burden of high speed flight within the atmosphere on the vehicle
- Increased fraction of low density hydrogen propellant

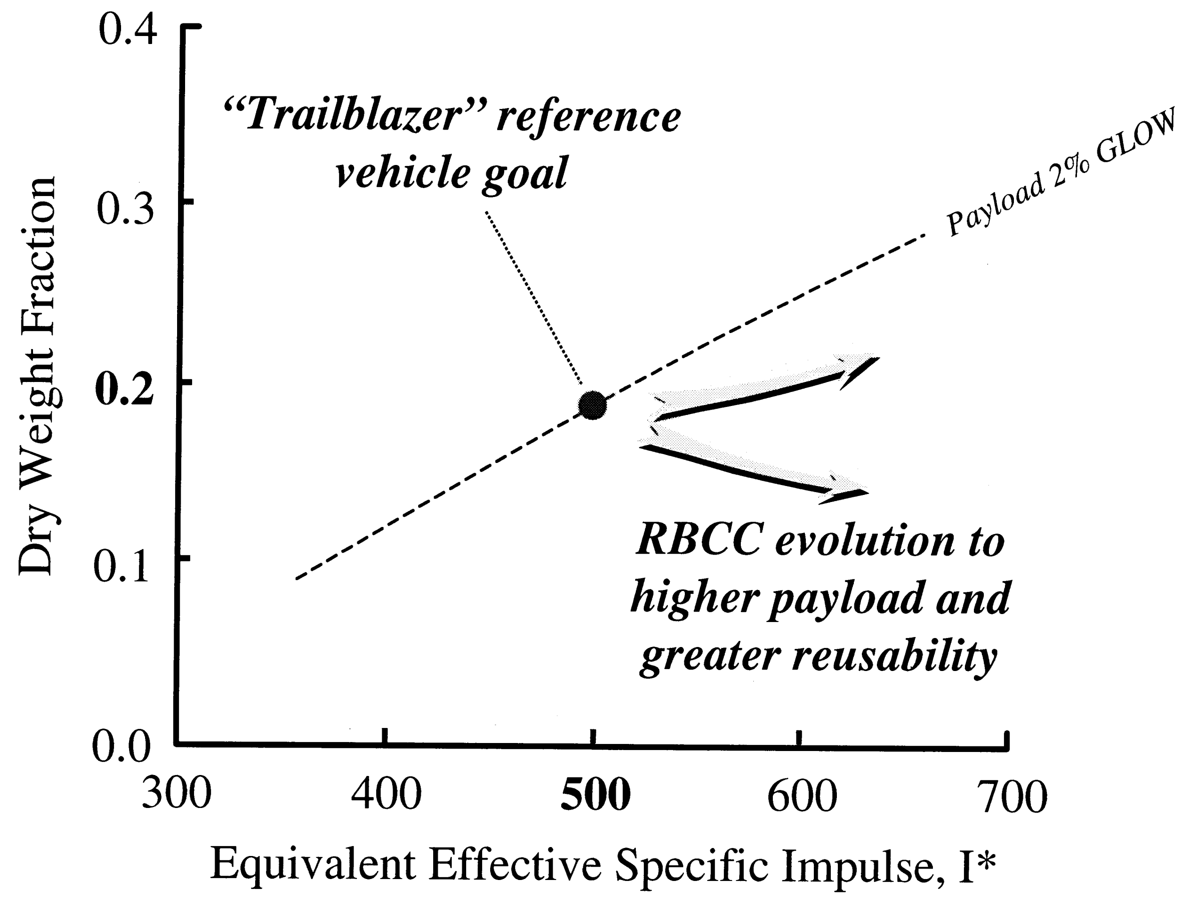
The "Trailblazer" Program



- NASA Lewis Research Center is developing RBCC engine technology in its "Trailblazer" program
- An objective of the program is to *manufacture* and *fly* a sub-scale, sub-orbital X-vehicle to demonstrate *system* performance goals
- Experiments and analysis are currently underway to mature the technologies required for this demonstration, and subsequent application of RBCC engine technology to the third pillar goals

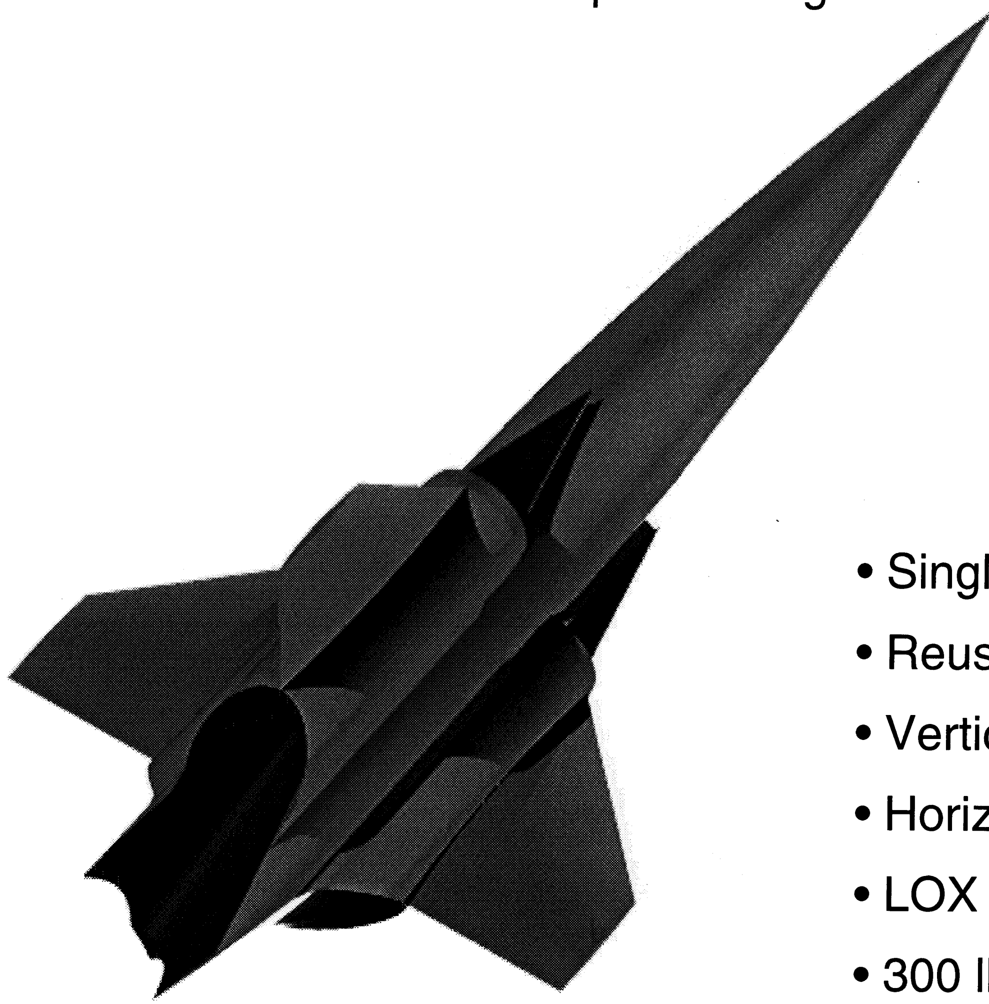
Trailblazer Performance Goals

RBCC-Powered SSTO Launch Vehicles can evolve to higher levels of performance after the first successful demonstration



Trailblazer Reference Vehicle

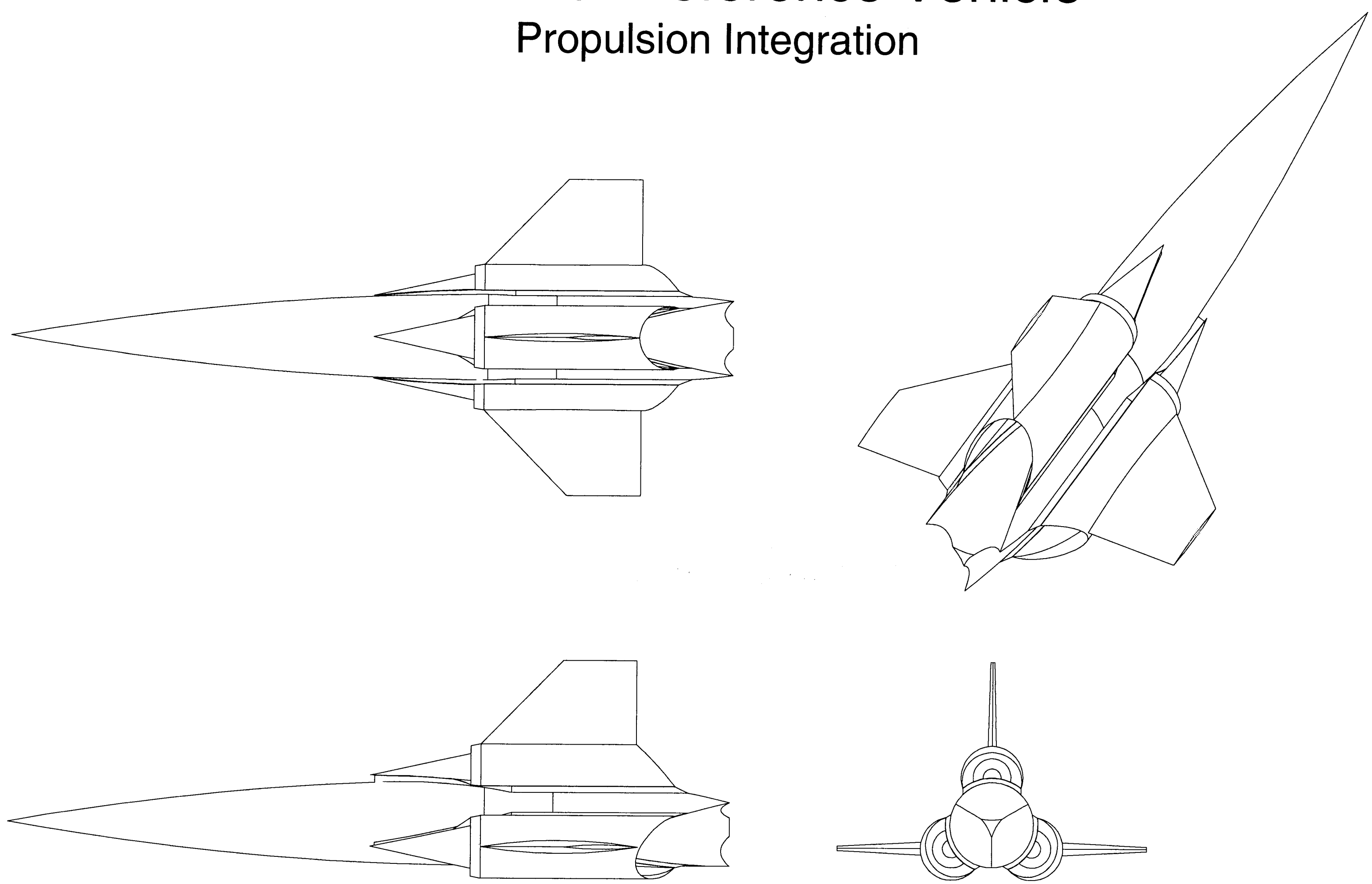
Conceptual Design



- Single stage to orbit
- Reusable
- Vertical lift-off
- Horizontal, unpowered landing
- LOX / LH2 Propellants
- 300 lb payload

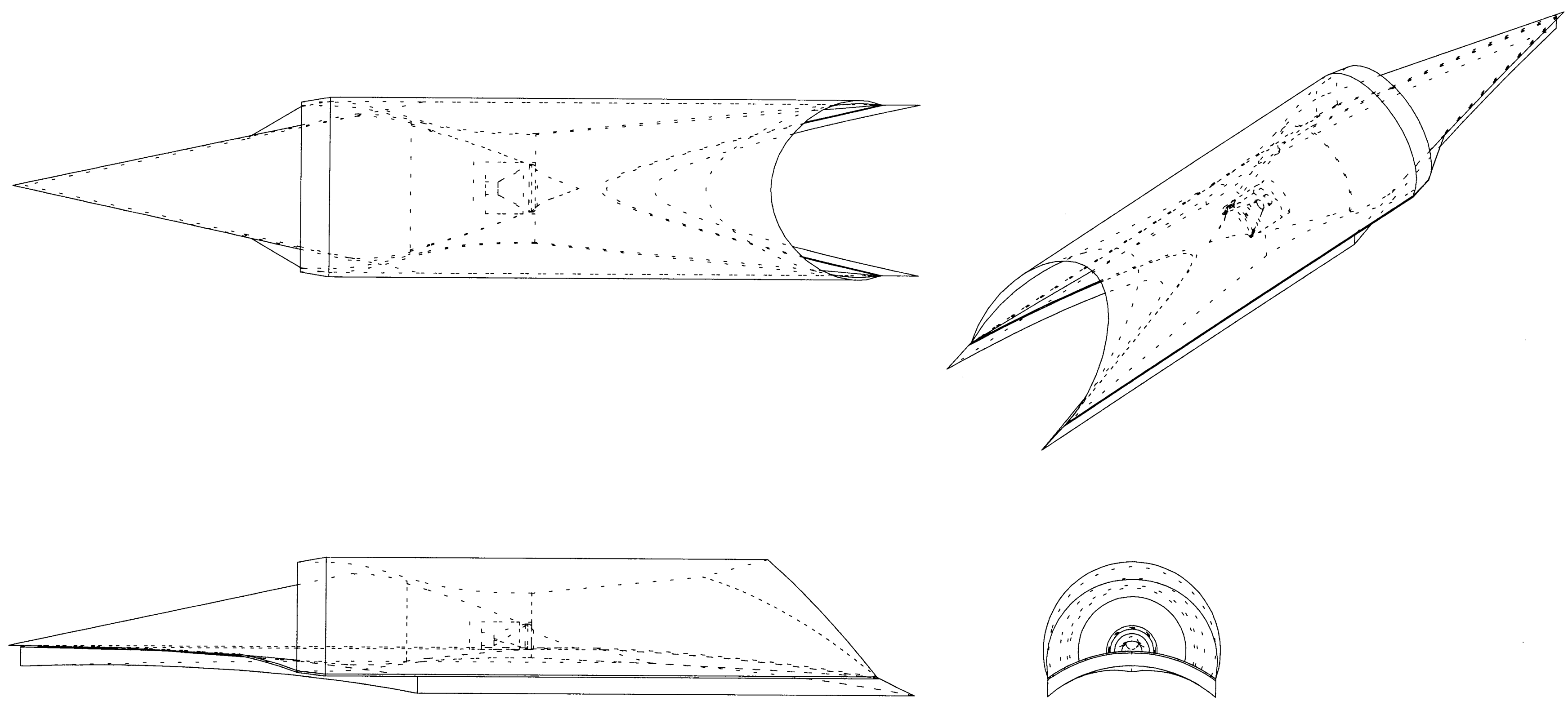
Trailblazer Reference Vehicle

Propulsion Integration



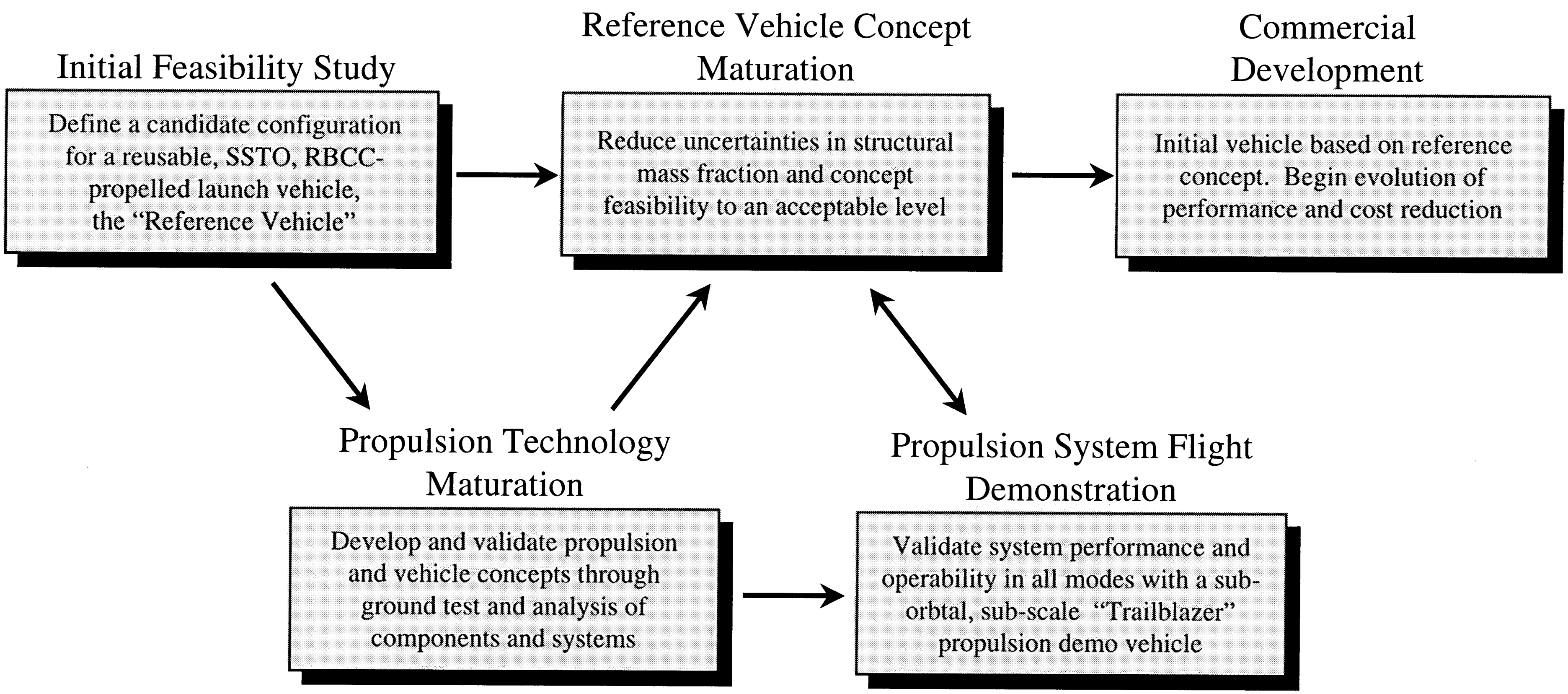
Trailblazer Project

Trailblazer Reference Vehicle Propulsion Pod



Trailblazer Project

Trailblazer Program Architecture



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BANTAM

Mark Klem
NASA Glenn Research Center
Cleveland, Ohio

Code R Goals

Orbit

Reduce the payload cost to orbit by an order of magnitude, from $10,000 to $1,000 per pound, within 10 years and by an additional order of magnitude, from thousands to hundreds of dollars per pound, within 25 years

In-Space

Achieve with 15 years,

A factor of ten reduction in the cost of Earth orbital transportation
A factor of two to three reduction in propulsion system mass and travel time required for planetary missions.

Within 25 years,

Enable bold new missions to the edge of the solar system and beyond by reducing travel times by on to two orders-of magnitude.

Bantam

- 150 Kg Payload
- 200 nmi due east
- Reusable Launch Vehicle SSTO or TSTO
- $1.5M per launch
- 12 launches per year

Bantam Elements

- Launch Services Contract - KSC led
  - Challenge to find launches for $1.5M in FY 99
- Users Workshop - GSFC led
  - Workshop with Codes S & Y to establish users requirements
- Virtual Vehicle Concepts - MSFC led
  - Vehicle concepts that will drive technology needs
  - Vehicle studies FY 99-00 and downselect at the end of FY 00
- Supporting Technologies - MSFC led
  - Technologies worked in FY 99-01 will support vehicle concepts
  - Technologies supporting more than one concept have priority
- Flight Demonstration - MSFC led
  - Vehicle concept selected in FY 00 will be taken to Pathfinder experiment in FY 02-04

Reusable Technology Investment Planning (RTIP)

* Develop a comprehensive, long term technology development and demonstration plan for each of the seven technology areas.

* Plans will be used as a mechanism for funding In-House NASA tasks and Industry bids under NRA 8-21, Cycle 2

* Approximately $20M/yr funds available (total)

* Plans must support Code R Goals 9 & 10 (attached)

* Propulsion plan should show how activities support IHPRPT goals (attached)

* Planning process should involve appropriate NASA Centers, other Government agencies, Academia, and Industry

* Each proposed technology must show how it contributes to reducing the cost of access to space for small payload launch systems

Virtual Vehicle Concept Development (VVCD)

* Develop a set of innovative Virtual Vehicle Concepts that have the potential of meeting the small payload metrics and customer requirements

* Mature Vehicle concepts to a level adequate to assess the probability of technical and economic success allowing for a down select to one or two vehicles in the late 2000 timeframe per Level II Roadmap

* Evaluate alternate concepts proposed by Industry, academia, and other government sources for possible addition to Vehicle Fleet

* Virtual Vehicles will serve as the Target for the technology development program and will identify advanced technologies for consideration/incorporation into the program

* Virtual Vehicle Fleet will be continually monitored for additions or deletions as technologies mature and new concepts are developed

VVCD cont´d

* Virtual Vehicle Concepts will be maintained and matured in-house NASA using an integrated design center approach with potential involvement from outside sources

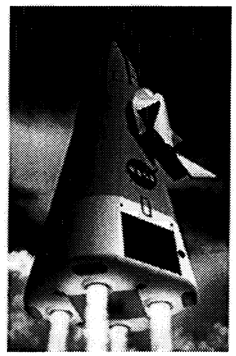
* Virtual Vehicle maturation will be based on:
  - Vehicle system design development
  - Assessment and management of technology risks
  - Feedback from Technology Development Program
  - Economic and cost analysis (development and operations)
  - Capability of meeting customer´s requirements
  - Synergy with other RLV programs (e.g. MSP)

* Develop a Future X proposal based on the Virtual Vehicle Concepts when appropriate

***** REMEMBER: COST IS KING ******

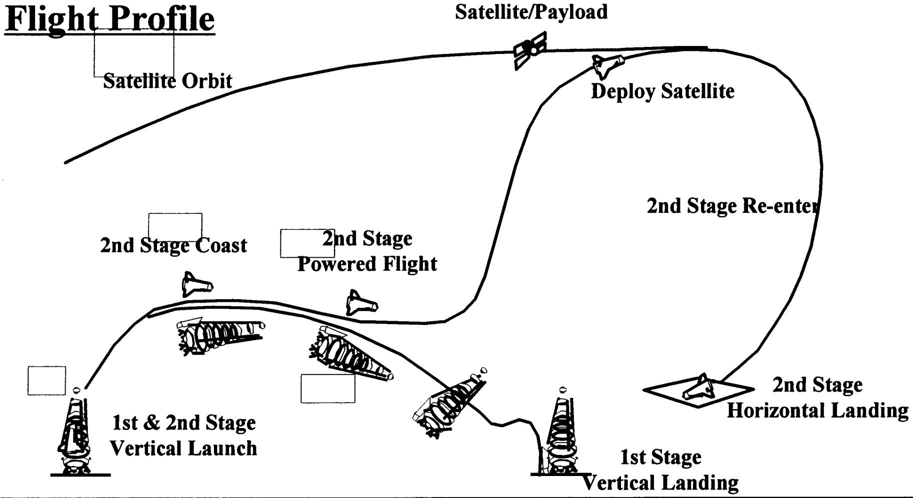
Concept 1 - VT/VL Vehicle

Vehicle Concept
- Fully Reusable Vertical Takeoff/Vertical Landing, 1st Stage
- Fully Reusable Horizontal Landing, Lifting Body 2nd Stage
- H2O2/JP GG Cycle 1st and 2nd Stage Propulsion Systems with E-D Nozzles
- LO2/JP & LO2/H2 Options



Benefits
- Reduced Operations Costs with Storable Propellants
- Improved Performance with E-D Nozzles and Lightweight Components

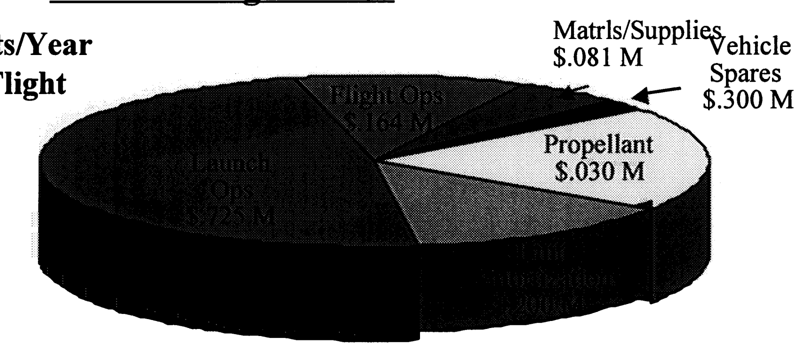
Flight Profile



Critical Technologies
- Robust, Lightweight, High Performance, H2O2/Kerosene Propulsion Systems
- Highly Throttlable Engines
- E-D Nozzles
- Advanced Thermal Protection Systems (TPS)
- Low Weight Tanks, Structures, and Components
- H2O2 Compatible Handling and Storage Facilities
- Automated Range Safety System
- Autonomous Launch and Landing Systems
- Automated Mission Planning

Cost Per Flight Goals

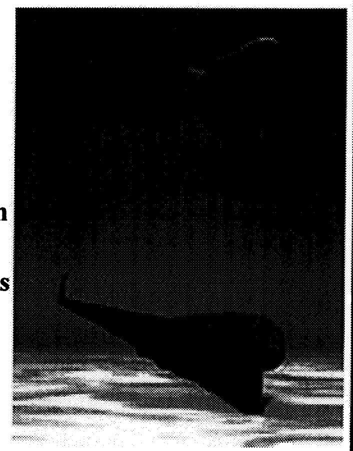
12 Flights/Year
$1.5 M/Flight



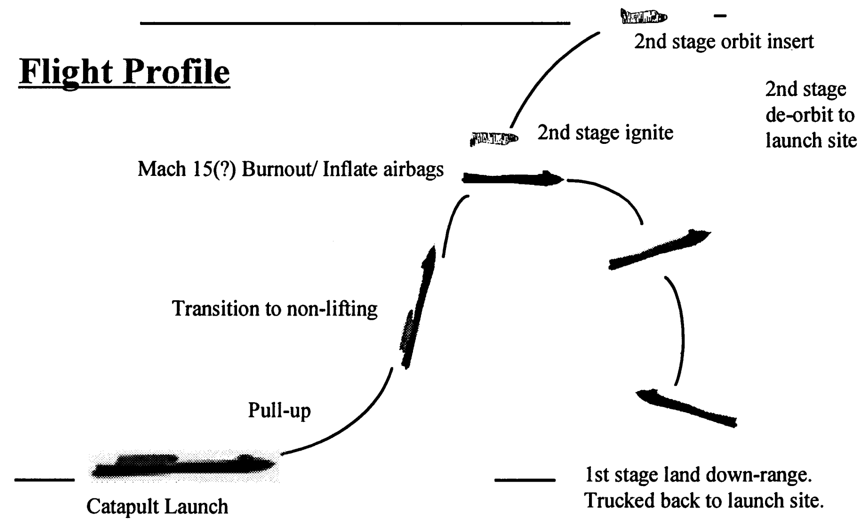
Concept 2 - HT / HL

Vehicle Concept

- Lifting Body Boost Stage
- Catapult Assist Take Off
- Two 'Racetrack' Aerospikes, RP/LOX or RP/H2O2, GG Cycle,
- Dorsal Fin & Small Wing Tip Fins
- HL20 Type 2nd Stage Inverted and Nested on Booster for Ascent
- Semi-Rigid Airbags Inflate to Separate Stages and Retain Booster Lee-ward Aerodynamic Shape for Re-entry



Flight Profile

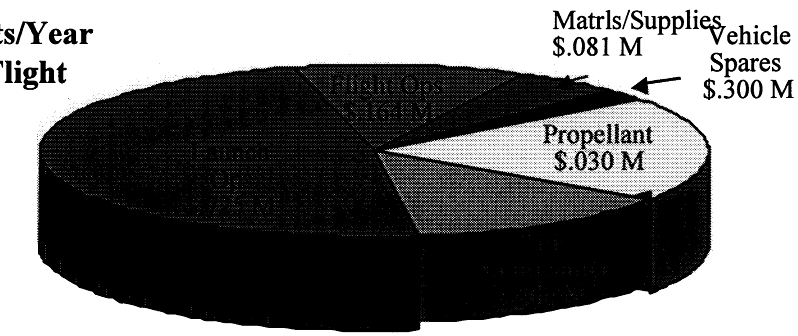


Critical Technologies

- Conformal Tanks
- Integrated TPS
- Racetrack Aerospikes, Composite(light weight) Nozzle
- Active Vehicle Control
- Airbags for Stage Separation & Booster Re-entry Aero
- Automatic Flight Termination
- Automatic Mission Planning
- Catapult Assist

Cost Per Flight Goals

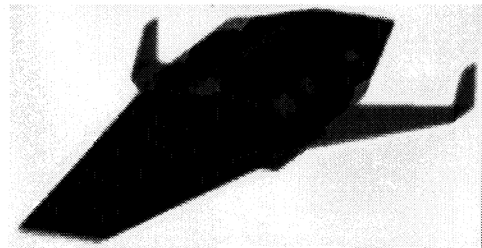
12 Flights/Year
$1.5 M/Flight



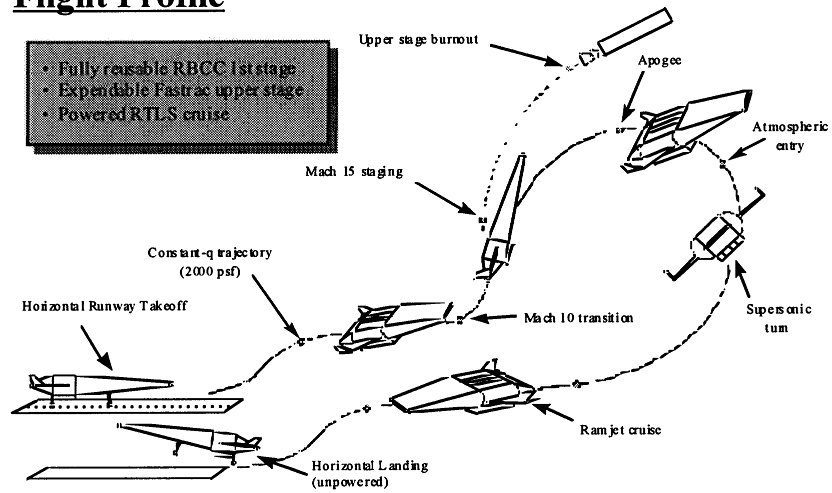
Concept 3a - HT / HL

Vehicle Concept

- Horizontal Takeoff/Horizontal Landing (HTHL) Rocket-Based Combined Cycle (RBCC) Reusable 1st-Stage Booster Vehicle
- Expendable, Low Thrust, Pressure-Fed FASTRAC Upper Stage Engine
- Powered Ramjet Cruise back to Launch Site
- Unpowered Landing
- 1st-Stage Propellants: LO2/LH2
- Vehicle Length: 89 feet
- Gross Weight: 106K lbm
- Dry Weight: 35K lbm



Flight Profile

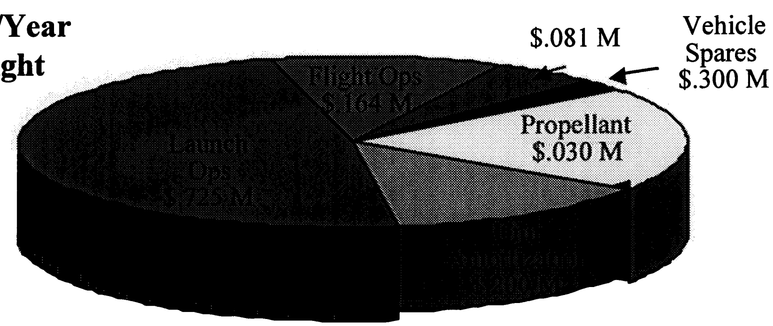


Critical Technologies

- Reusable 1st-Stage
  - RBCC Propulsion System
  - LOX Composite Tanks
  - Advanced TPS Systems (SHARP, TUFI, AFRSI)
  - Autonomous Launch & Landing System
  - Autonomous Flight Termination System (AFTS)
- Expendable 2nd-Stage
  - Low Cost Expendable Upper Stage Hardware
  - Small Scale FASTRAC Engine
  - Low Cost Upper Stage Avionics

Cost Per Flight Goals

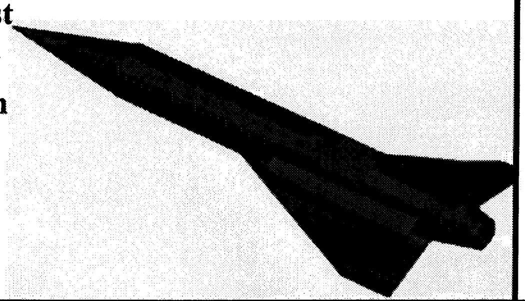
12 Flights/Year
$1.5 M/Flight



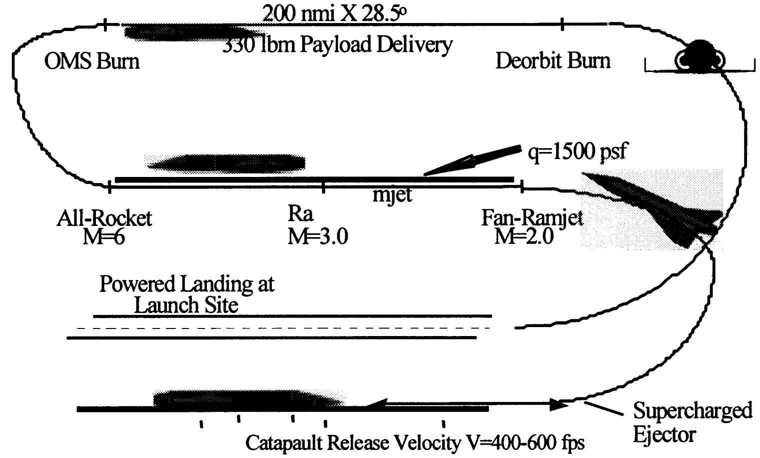
Concept 3b - HT / HL

Vehicle Concept

- **Single-Stage, Fully Reusable Vehicle Concept with Launch Assist**
  - **HTHL RBCC Vehicle**
  - **Powered Landing at Launch Site**
  - **Catapult Launch Assist**
- **Vehicle Length: ~150 feet**
- **Gross Weight: ~400K lbm**
- **Dry Weight (1st-Stage): ~50K lbm**

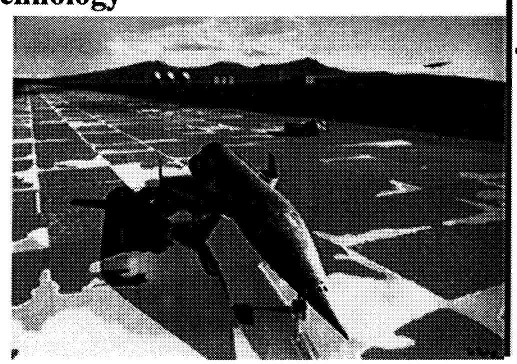


Flight Profile



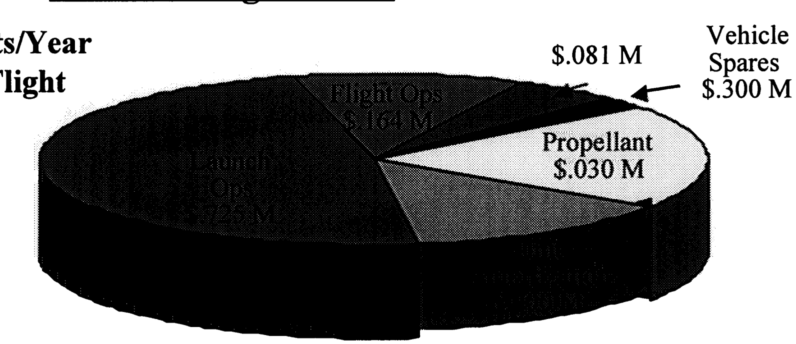
Critical Technologies

- **Reusable 1st-Stage**
  - **LO2/LH2 RBCC Engine - Supercharged Ejector Ramjet**
  - **Catapult Launch Assist**
  - **Integral Composite Tanks**
  - **Lightweight Subsystem Technology**
  - **Lightweight Materials**
    - **Graphite/PEEK**
    - **Titanium-Aluminide**



Cost Per Flight Goals

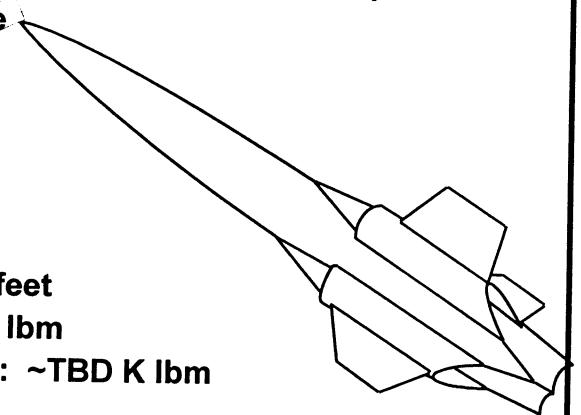
12 Flights/Year
$1.5 M/Flight



VC-3c: VT / HL - Concept 3c

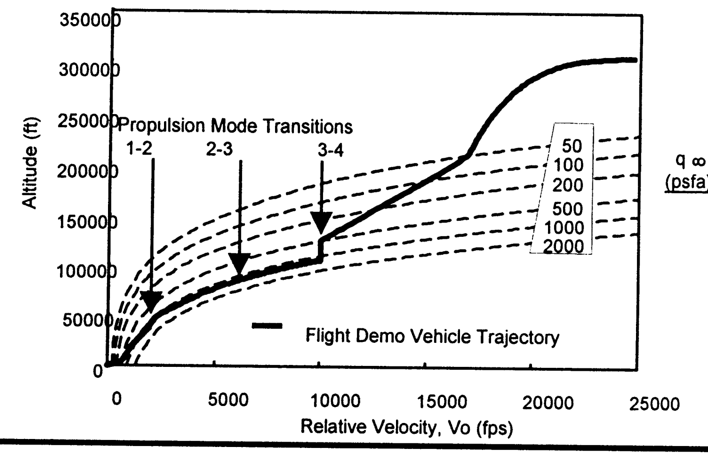
Vehicle Concept

- Single-Stage, Fully Reusable Vehicle Concept
- VTHL RBCC Vehicle



- Vehicle Length: ~100 feet
- Gross Weight: ~100 K lbm
- Dry Weight (1st-Stage): ~TBD K lbm

Flight Profile



Critical Technologies

- LO2/LH2 RBCC Propulsion System
- Integrated Vehicle/Propulsion System
  - Composite Tanks
  - Lightweight Subsystem Technology
  - Lightweight Materials

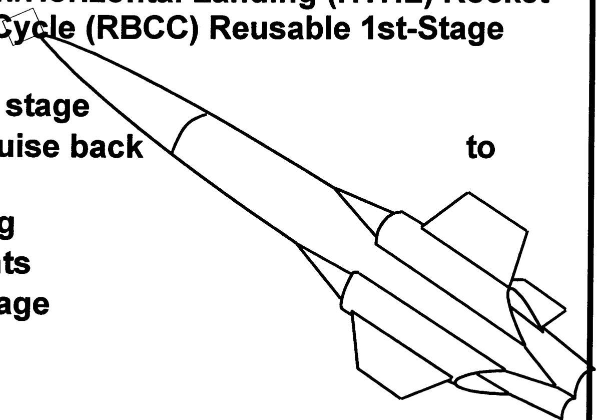
Cost Per Flight Goals

12 Flights/Year
$1.5 M/Flight

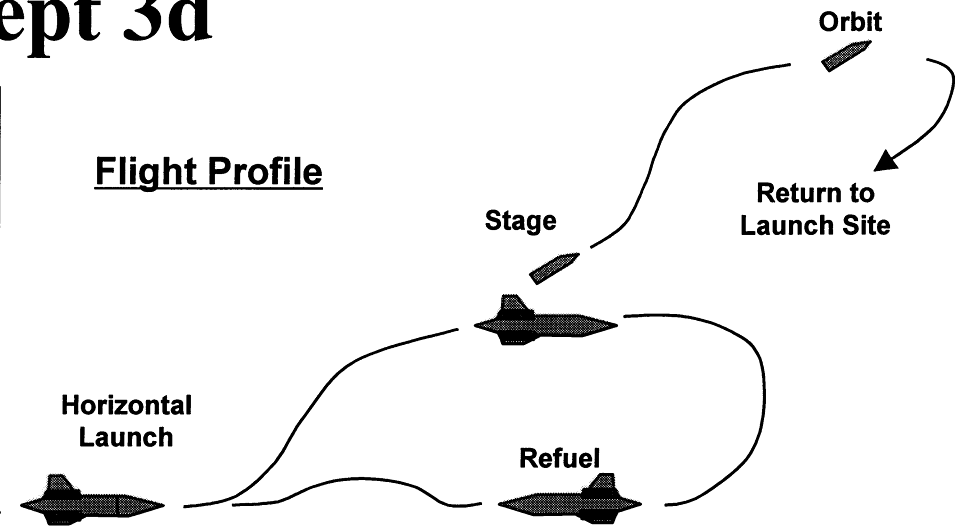
VC-3d: HT / HL - Concept 3d

Vehicle Concept

- Horizontal Take-Off/Horizontal Landing (HTHL) Rocket-Based Combined Cycle (RBCC) Reusable 1st-Stage Booster Vehicle
- Expendable upper stage
- Powered ramjet cruise back to launch site
- Unpowered landing
- LO2/LH2 propellants
- Launch assist/2 stage



Flight Profile



Critical Technologies

- LO2/LH2 RBCC Propulsion System
- Integrated Vehicle/Propulsion System
  - Composite Tanks
  - Lightweight Subsystem Technology
  - Lightweight Materials
  - Vehicle & Propulsion Controls
- Expendable second stage

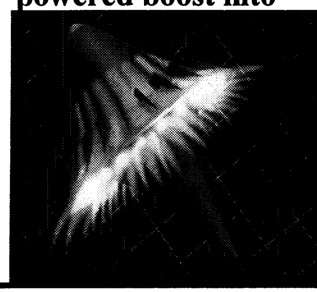
Cost Per Flight Goals

12 Flights/Year
$1.5 M/Flight

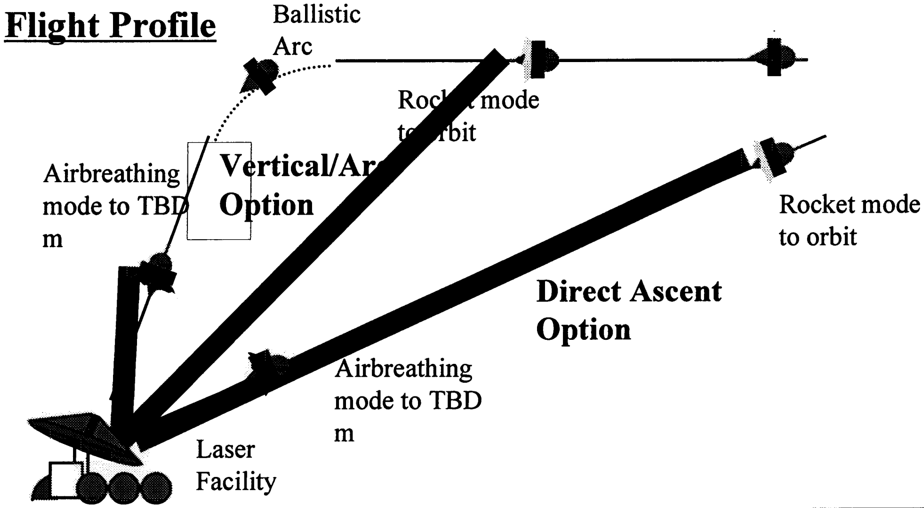
Concept 4 - Laser Lightcraft

Vehicle Concept

- **Single stage to orbit laser-powered launch vehicle**
- **Thrust produced by pulsed laser-induced blast wave propagation & expansion**
- **Infinite specific impulse during ascent thru atmosphere**
- **Onboard propellant used for final laser-powered boost into space & orbit**
- **1st stage: 100 MW - 1 GW "reusable" pulsed CO2 laser**
- **Gross mass: ~1,000 kg**
- **Dry mass: ~200 kg**
- **Vehicle diameter: 1 - 2 meters**



Flight Profile



Critical Technologies

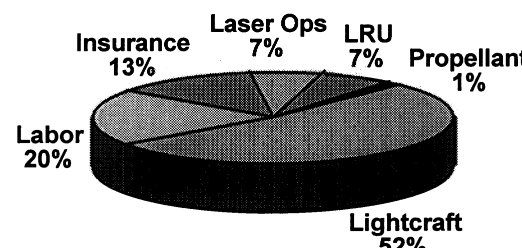
- **Laser "1st-Stage"**
  - Upgrades to 100 MW - 1 GW (inter-program cost sharing)
  - Pointing, tracking & stability
  - Frequency compensation/correction with altitude
- **Lightcraft "2nd/Upper-Stage"**
  - Lightweight materials
  - Inverse-bremstrahlung heating & ablation
  - Rocket-mode propellant injection & heating
  - Airbreathing/rocket mode thrust cavity gas dynamics
  - Propellant storage & feed technology

Recurring Costs

Cost Breakdown ($M)

Propellant	0.010
Labor	0.150
LRU	0.050
Lightcraft	0.400
Insurance	0.100
Laser Ops	0.050

Based on 150 kg payload, 24 flights/year

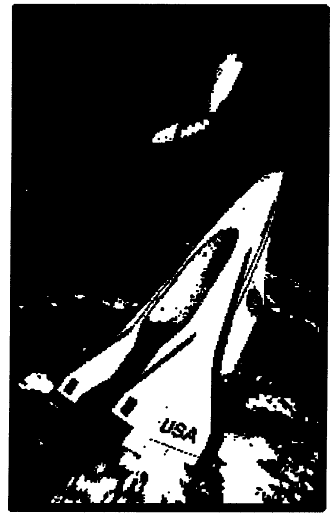


Recurring Cost per Flight = $0.760 M

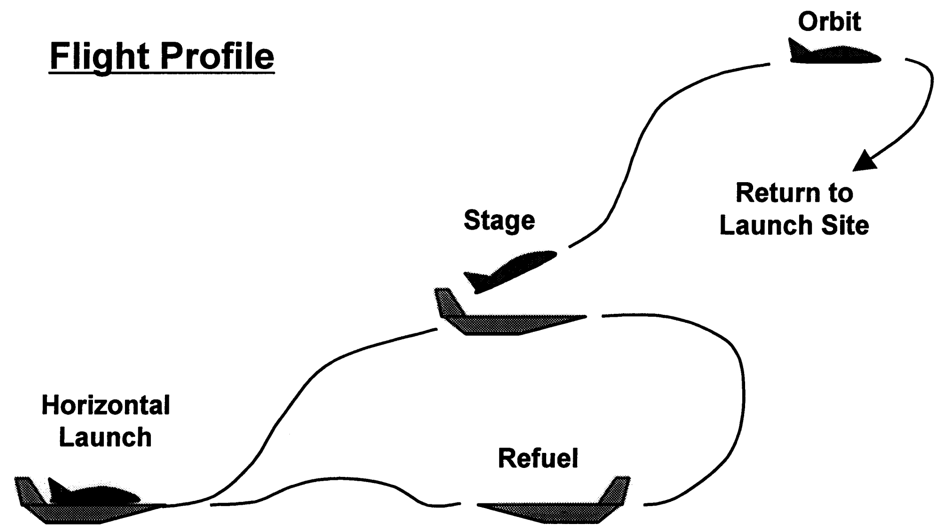
VC-5: HT / HL - Concept 5

Vehicle Concept

- Turbine-Based Combined Cycle Propulsion System
- First-stage demonstrator:
  - Mach 5 or greater
  - Turbine-powered take-off/landing
  - 10 Klb gross weight
  - 40 ft long
  - Reusable



Flight Profile



Critical Technologies

- Turbine-Based Combined Cycle Propulsion
  - Propulsion components (from inlet to nozzle)
  - Integrated propulsion system technologies
  - Airframe integration
  - Variable geometry actuation/sealing/thermal
- Integrated vehicle/propulsion control
- Vehicle TPS

Cost Per Flight Goals

12 Flights/Year
$1.5 M/Flight

Concept 6- Bimese Launch Concept for Bantam

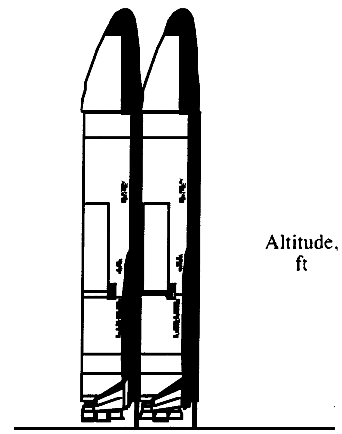
Point of Contact: Theodore A. Talay, 757-864-4505, t.a.talay@larc.nasa.gov Vehicle Analysis Branch, NASA Langley Research Center

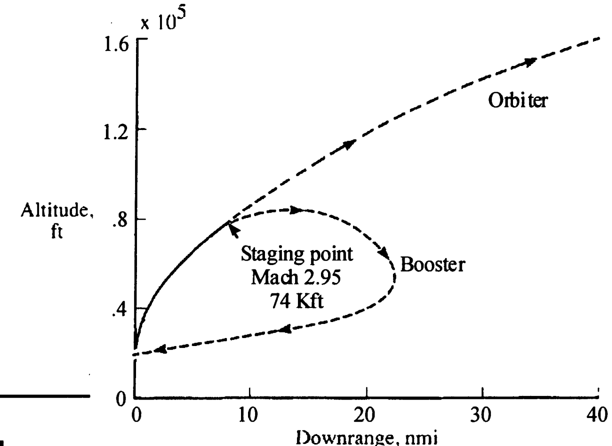
Vehicle Concept

- Fully Reusable Vertical Takeoff/Horizontal Landing Stages
- LOX/RP-1 Propulsion
  Isp = 347 sec; T/W = 110
- LOX/RP-1 & LOX/LH2 options

Benefits

- Identical stages
  Development based on one stage only. Reduced operations compared to non-identical stages.
- Low staging Mach number (2.95) allows glideback to launch site (rapid turnaround, no added return propulsion requirements)
- Potential boosters for medium-lift launch vehicle





Wgross = 298 Klb
Wdry = 29 Klb
Body length = 58 ft

Bantam Concept

Critical Technologies

- Robust, Lightweight, High Performance LOX/RP-1 Propulsion Systems
- Highly Throttleable Engines
- Advanced Thermal Protection Systems (TPS)
- Low Weight Tanks, Structures, and Components
- Simple, Operable Crossfeed System
- Advanced GNC Systems for Glideback
- Autonomous Launch and Landing Systems
- Automated Mission Planning

THERMAL PROTECTION SYSTEM DESIGN AND DEVELOPMENT FOR THE X-38

T. John Kowal
Lyndon B. Johnson Space Center
Houston, Texas

Crew Return Vehicle

An element of the International Space Station (ISS)

Three Scenarios

- ISS catastrophe
- Emergency medical evacuation
- Period of Space Shuttle unavailability

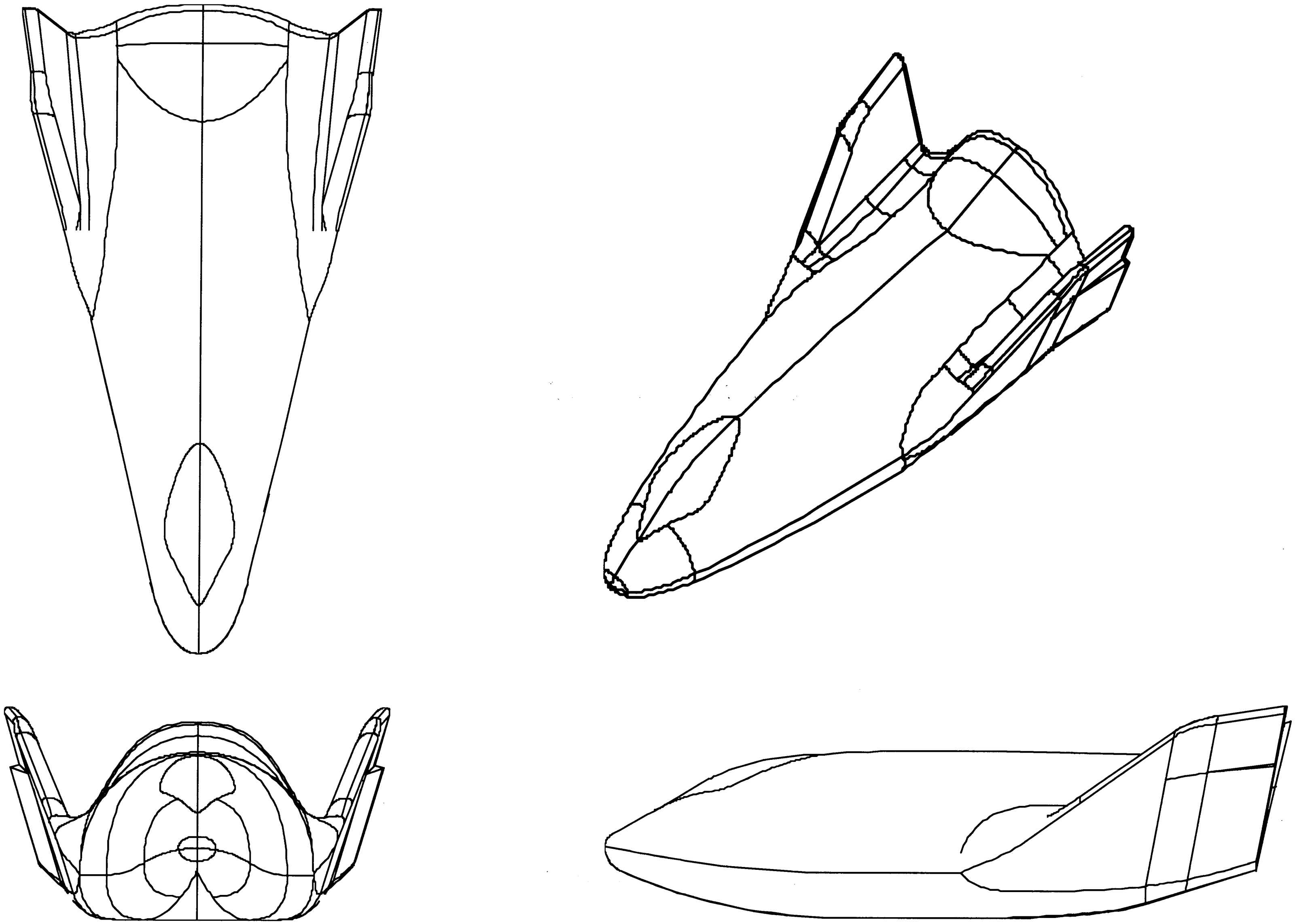
X-38 Program Overview

Program Purpose:

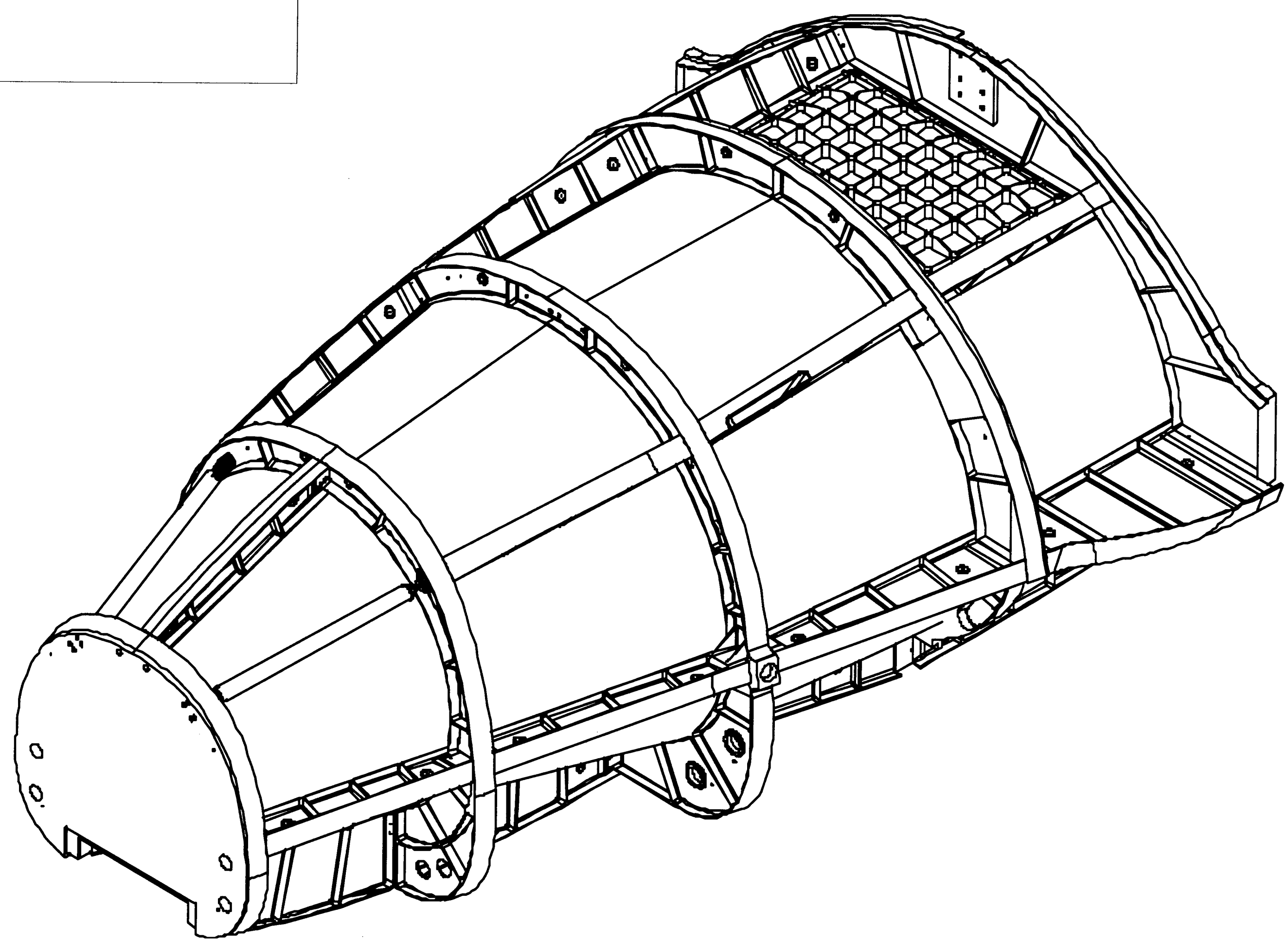
- To greatly reduce the costs and schedule for the development of Crew Return Vehicles (CRV's) and Crew Transfer Vehicles (CTV's) through the use of the rapid development methodology associated with an X-project

- **Ground Testing**
- **Atmospheric Testing**
- **Space Flight Testing**

X-38 V-201 Outer Mold Line

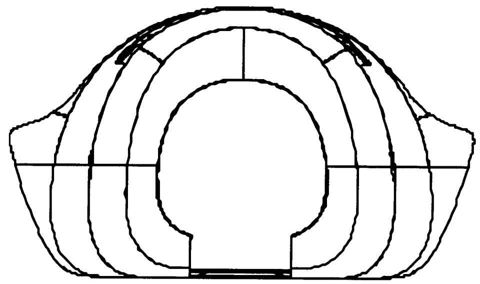


Forward Fuselage (Cabin)

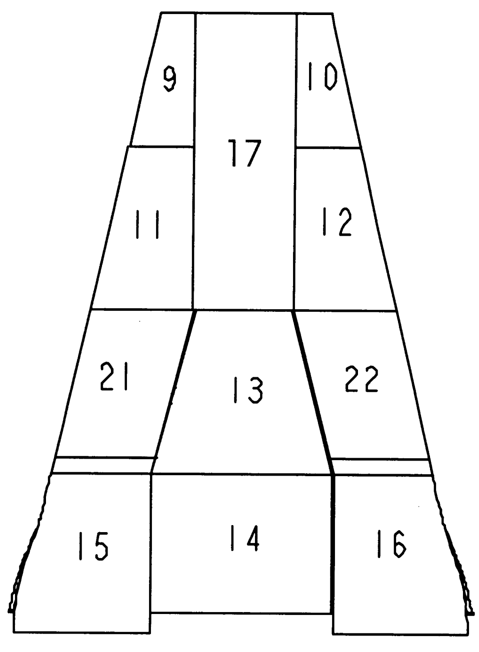


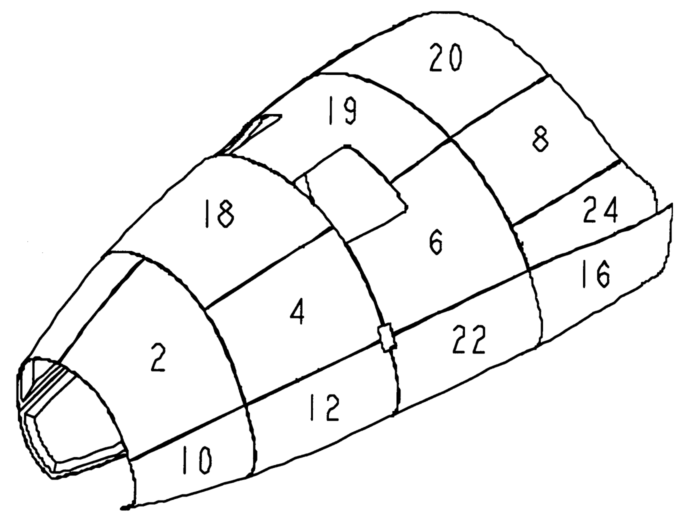
Aeroshell

FRONT VIEW



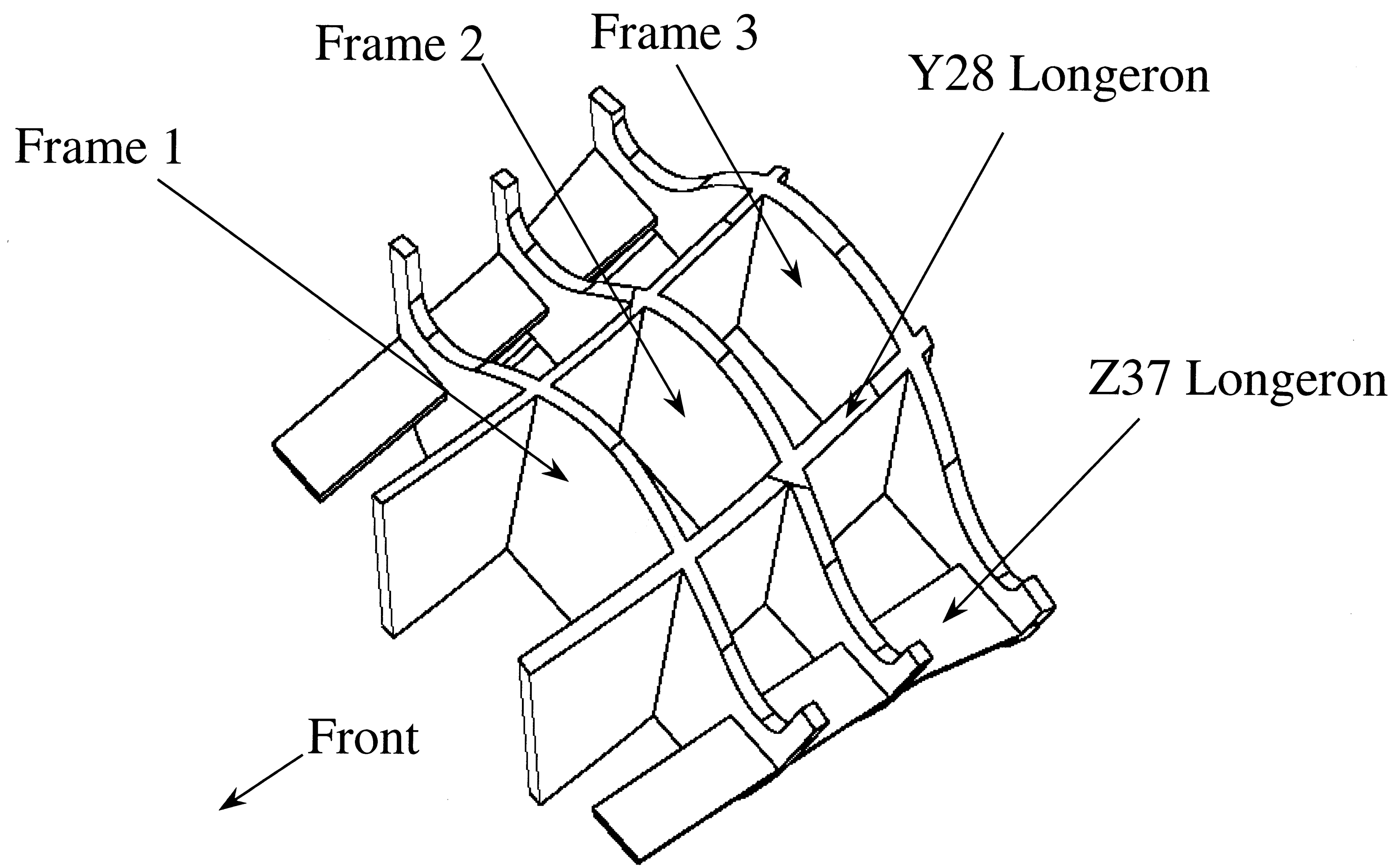
BOTTOM VIEW





Composite panel layout
– forward fuselage

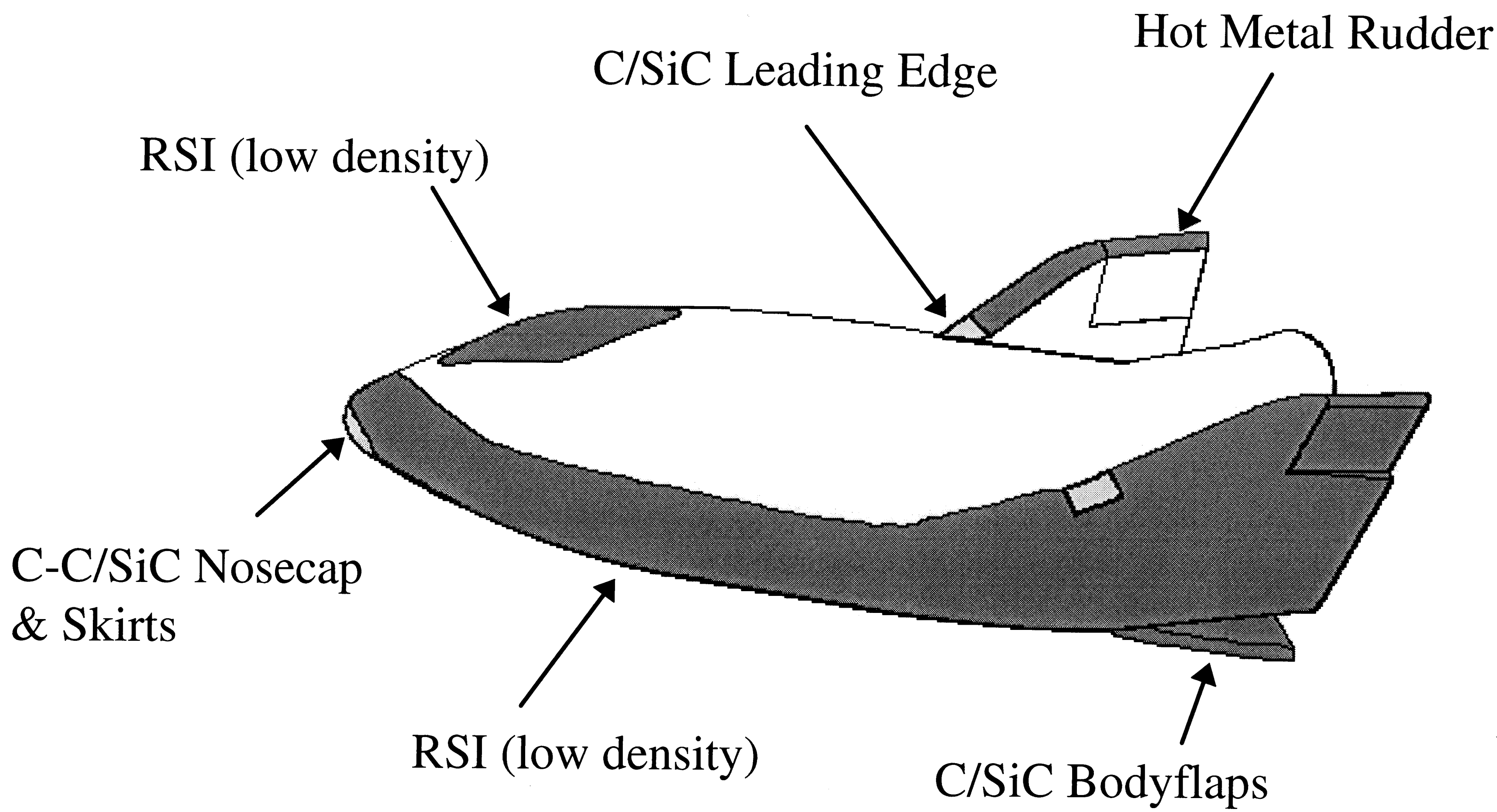
Aft Fuselage Design



TPS Configuration

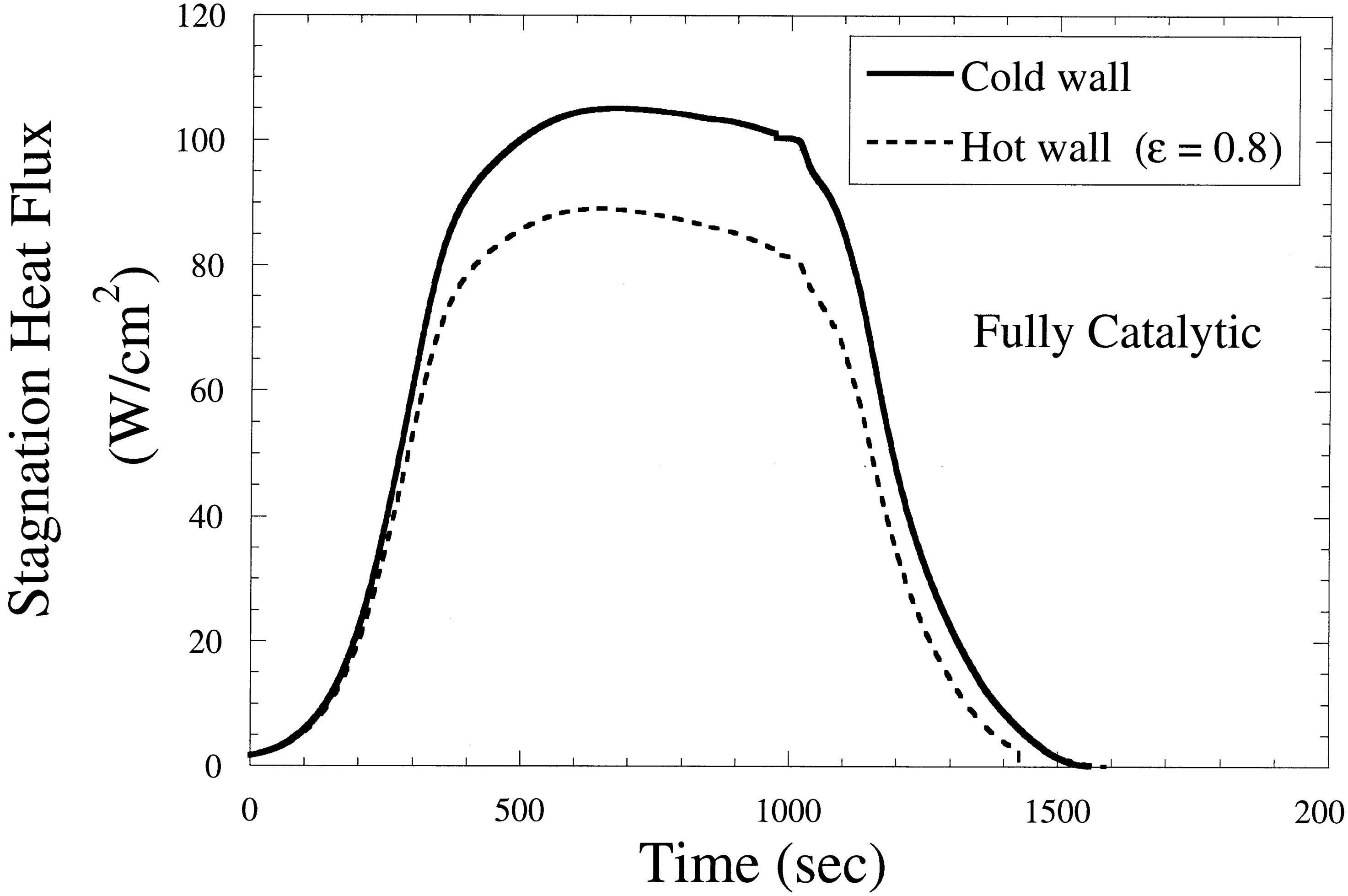
- Nose area
  - Carbon/Silicon Carbide (C/SiC)
    - Nosecap provided by DLR (Germany)
    - Nose skirts (2) provided by DASA (Germany)
    - Chin panel provided by MAN Technologie
- Windward Acreage
  - Low density advanced tile
    - AETB-8
  - C/SiC Body flaps
    - Provided by MAN Technologie (Germany)
- Leeward Acreage
  - Quilted blankets
    - Nextel 312 outer cover
    - Silica or Alumina batting
  - Needled Felt Blankets
    - Polybenzimidazole (PBI)/Kevlar/Nomex

TPS Overview



Reference Heating

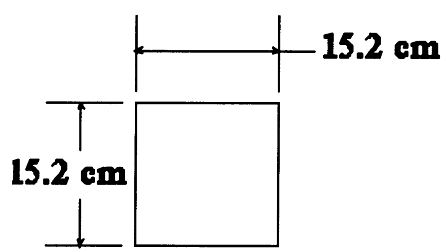
X-38 Stagnation Point Heating
Cycle 7.1 Trajectory



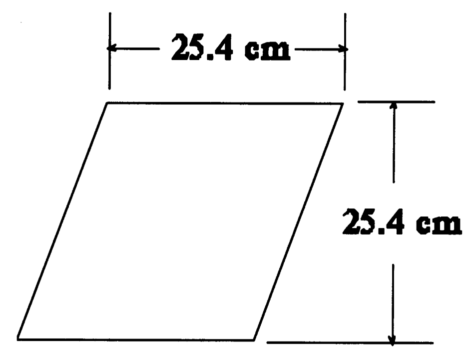
Tile System Description

Materials derived from Space Shuttle Tile System

- Advanced substrate material
  - Higher strength allows larger tiles
    - ⇒ Reduces tile count
- Higher durability coating



Typical Space Shuttle Tile

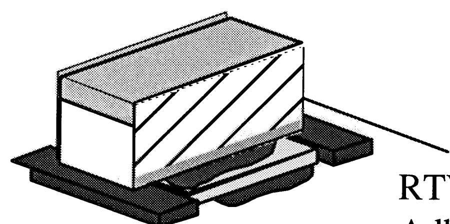


Typical X-38 Tile

Tile System Comparison

Tile system modified to simplify installation

- System developed for Aeroassist Flight Experiment
- Changes from baseline Space Shuttle System:
  - Eliminates filler bar
  - Full footprint strain isolation pad (SIP)
  - Ceramic gap fillers installed in all gaps



Space Shuttle Orbiter
TPS Tile Configuration

Ceramic Fabric Gap Filler (all gaps)

Densified Layer

Full Footprint SIP

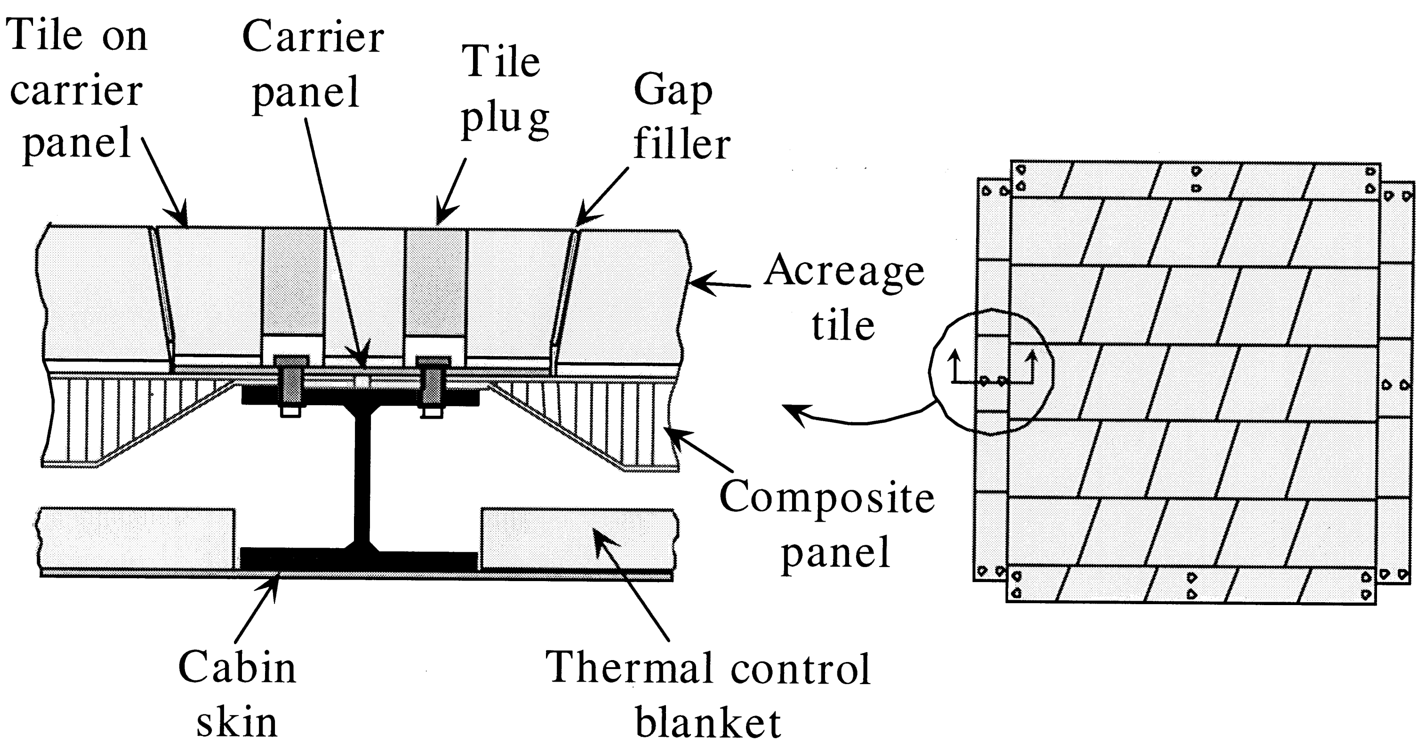
RTV Adhesive

X-38 TPS Tile Configuration

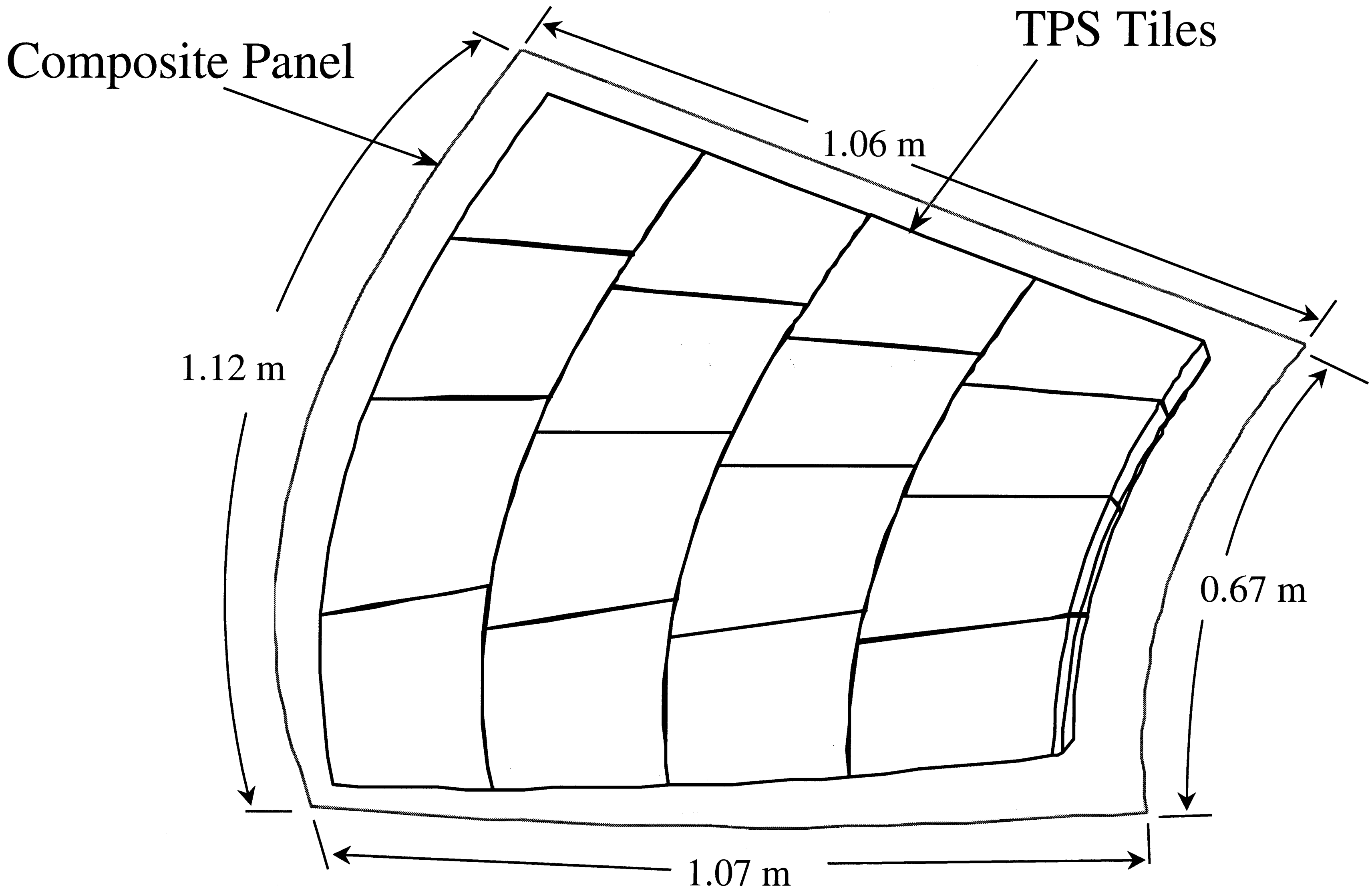
Composite Panel Joint

Vehicle requires ability to remove aeroshell panels quickly

– Necessitates use of tile carrier panel to access fasteners



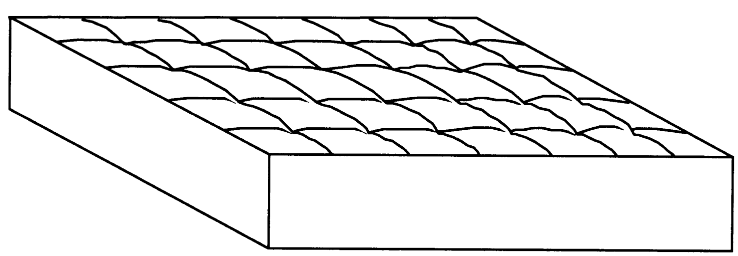
Aeroshell Panel 9 TPS

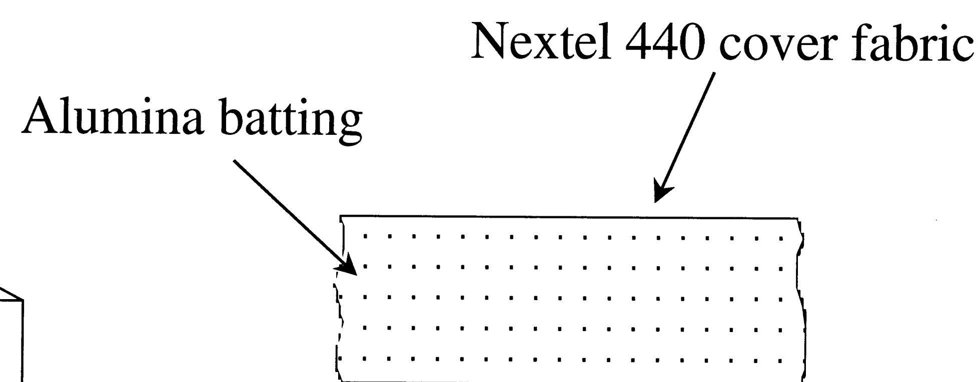


Blanket Selection

Quilted ceramic blanket

- Original baseline
- High temperature AFRSI (HTA)
  - Derivative of Orbiter AFRSI
  - Upgraded cover and insulation material



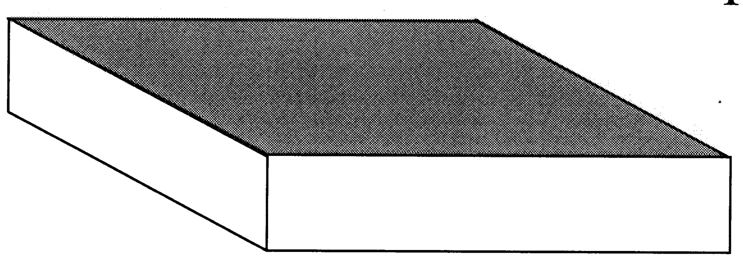


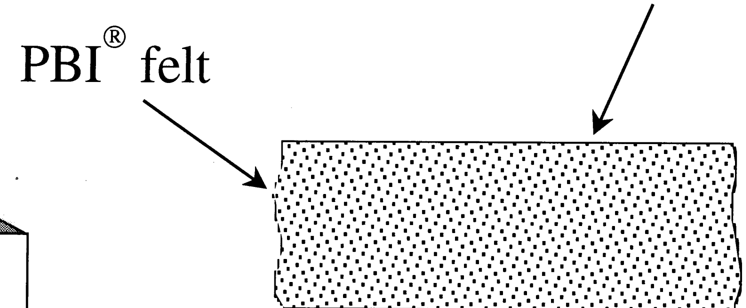
Blanket cross-section

Blanket Selection

Felt blanket

- Reduction in heating allowed for consideration
- Derivative of Orbiter FRSI
  - Needled polybenzimidazole (PBI®) felt
  - Coating investigation in work



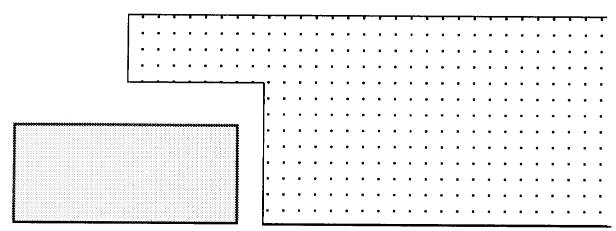


Blanket cross-section

Parafoil Line TPS

Parafoil lines routed on exterior of structure

- Requires TPS which also allows parafoil deployment
- Concept Has been tested for thermal protection and deployment

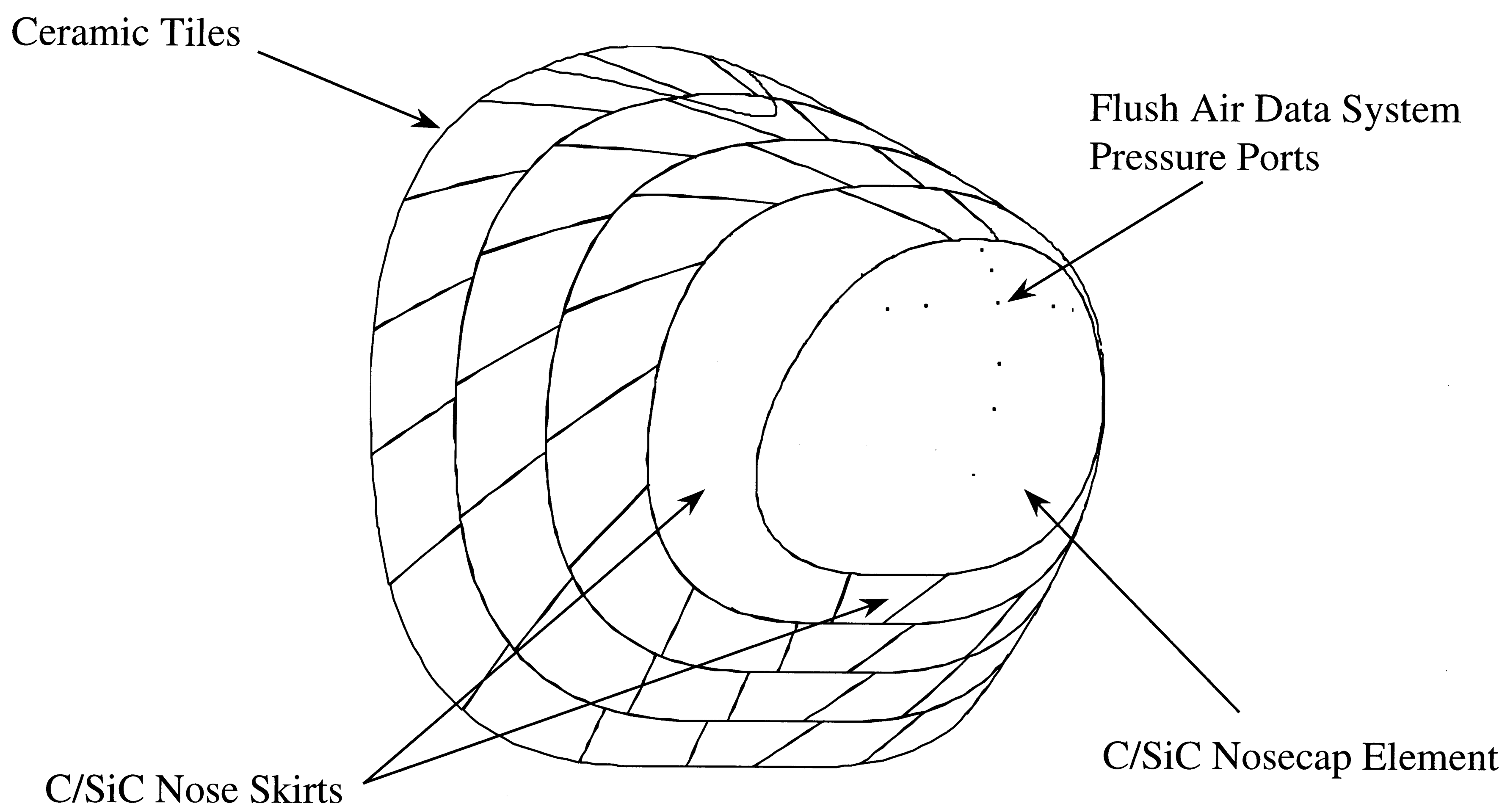


Nosecap

C-C/SiC nosecap element

- Provided by DLR
  - Liquid silicon infiltration (LSI) process
- Size is approximately 750 mm by 750 mm
- Incorporates flush air data system (FADS) pressure ports

Nosecap


Ceramic Tiles
Flush Air Data System
Pressure Ports
C/SiC Nose Skirts
C/SiC Nosecap Element

Body Flaps

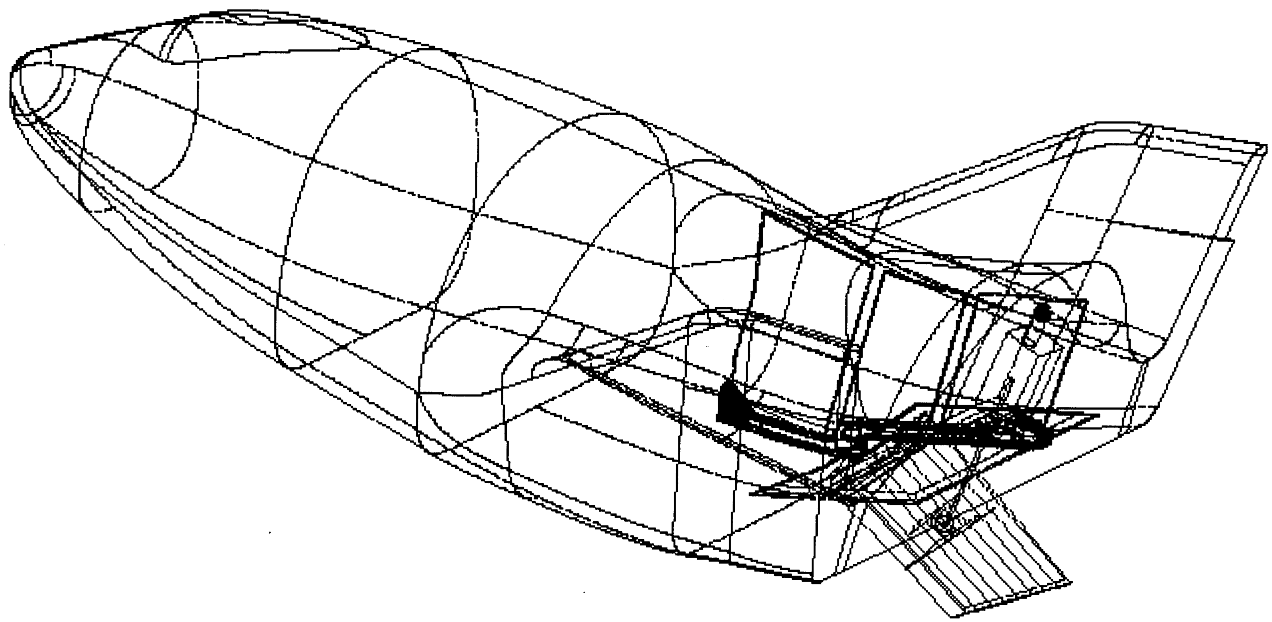
C/SiC bodyflaps

- Provided by MAN Technologie
  - Liquid polymer impregnation (LPI)
  - Chemical vapor infiltration (CVI)
- Size is approximately 740 mm by 640 mm

⇒ Hingeline Seal

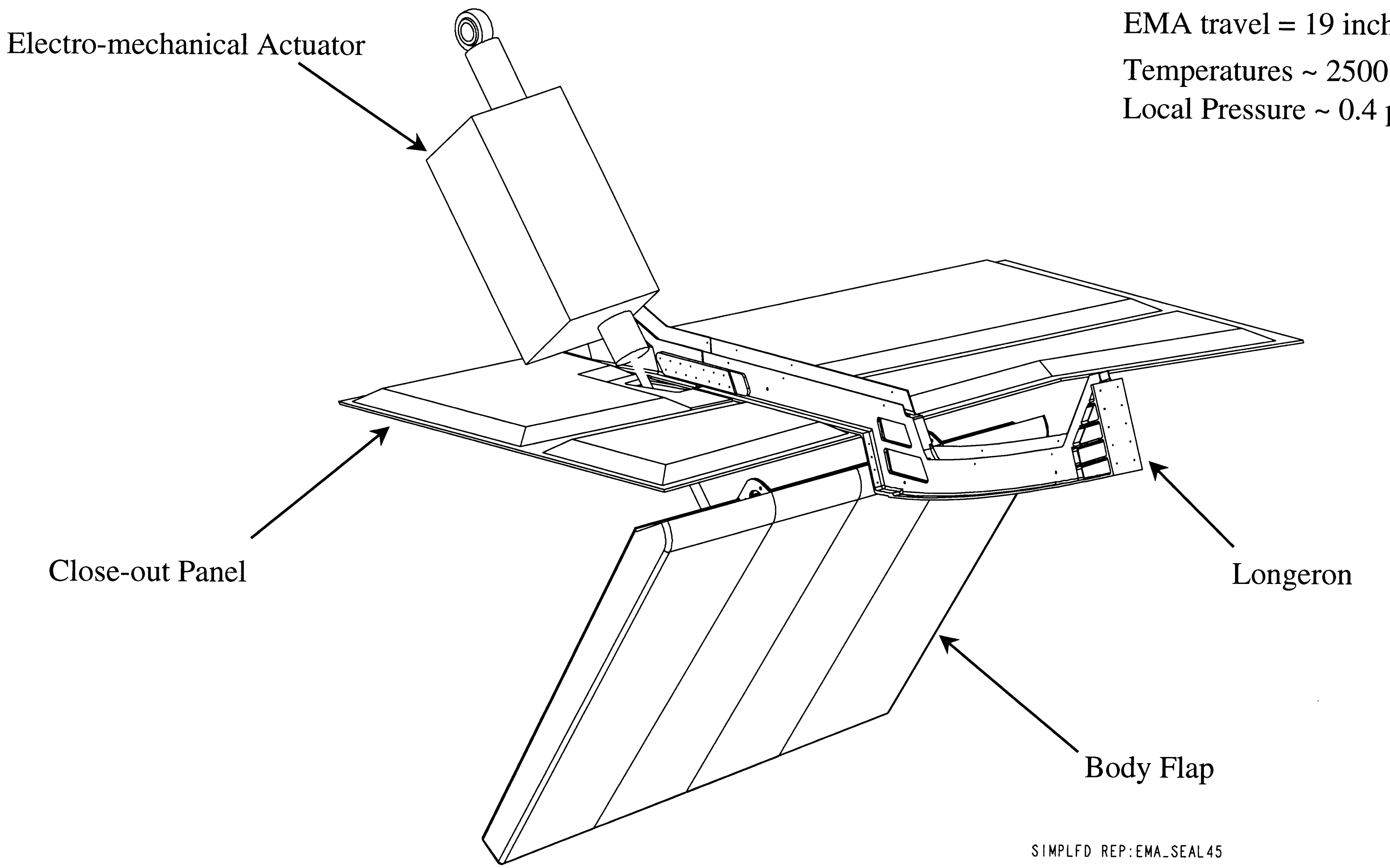
⇒ Electro-mechanical actuator (EMA) seal

Body Flap



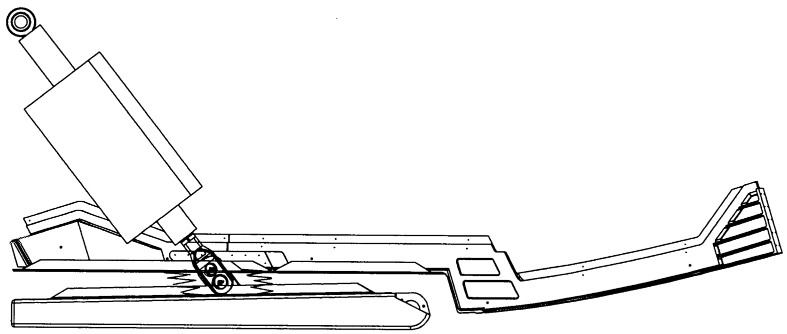
Bodyflap Configuration

EMA travel = 19 inches
Temperatures ~ 2500° F
Local Pressure ~ 0.4 psi

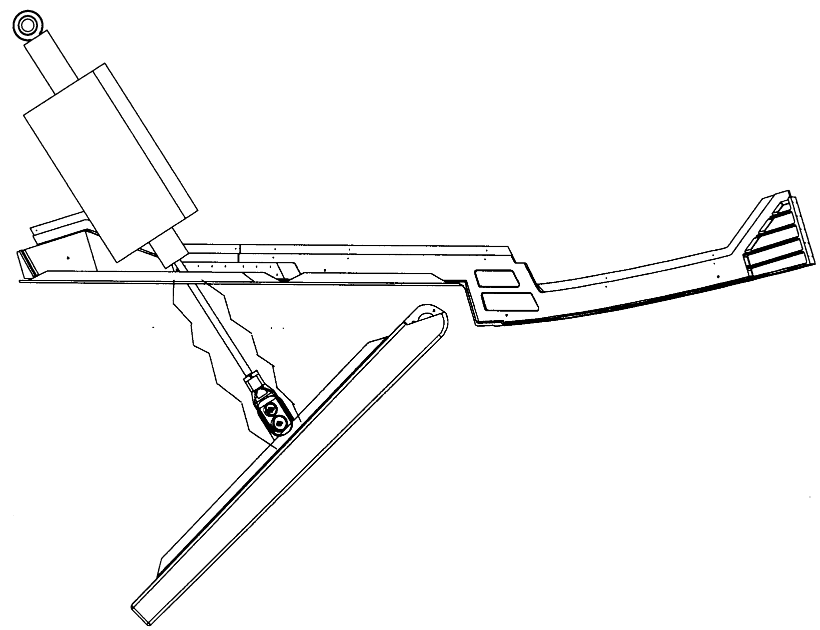


Body Flap EMA Seal

Bellows Seal Concept



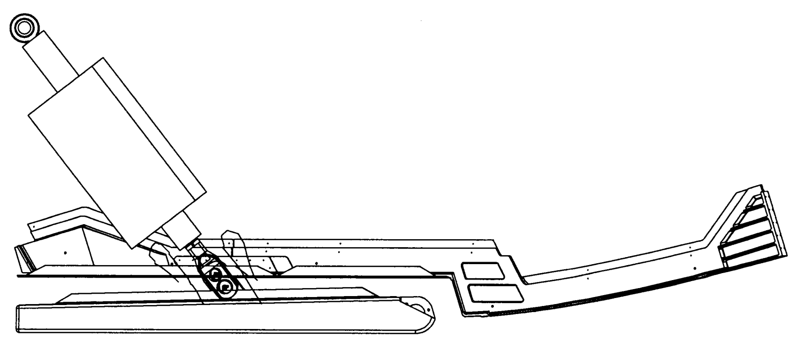
0° Deflection



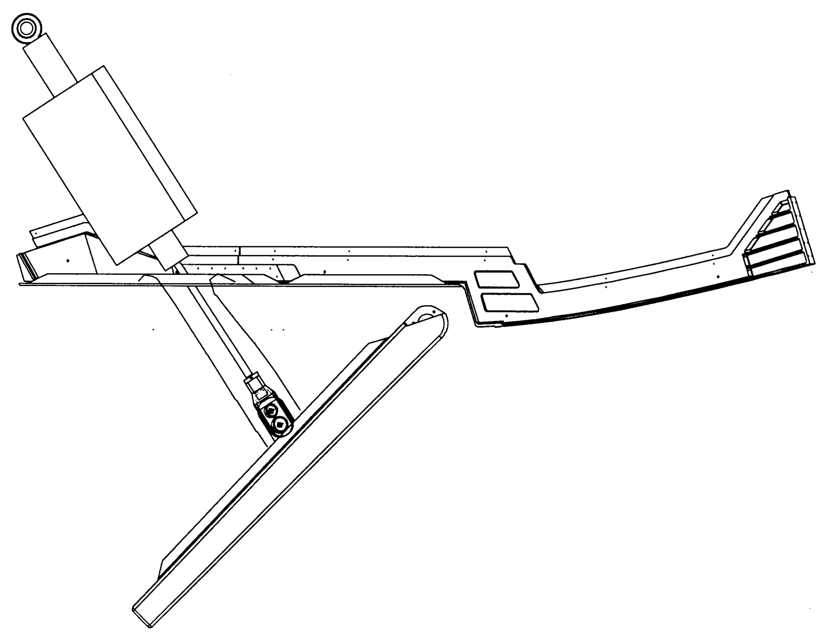
45° Deflection

Body Flap EMA Seal

"Rolling Sock" Concept



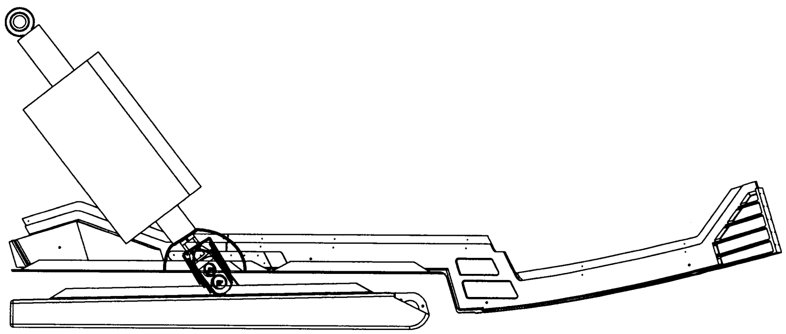
0° Deflection



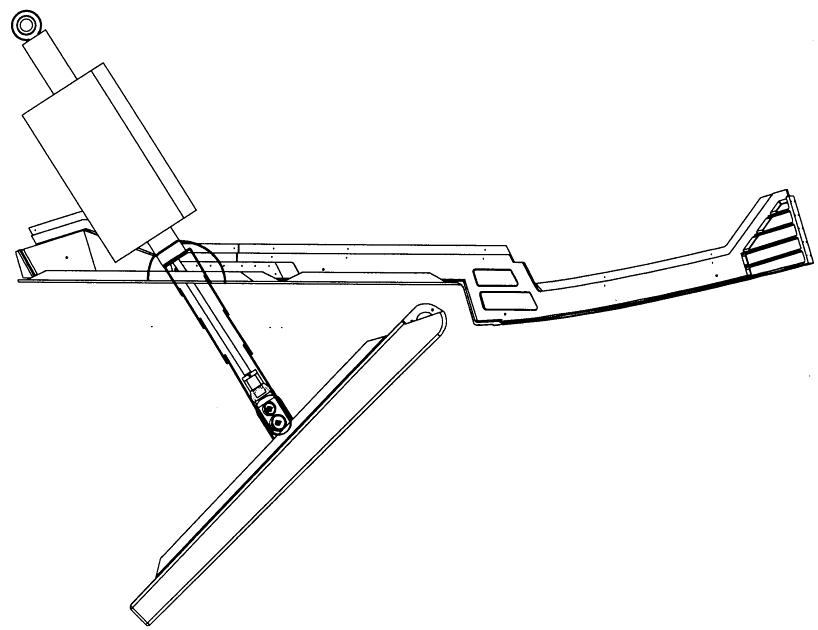
45° Deflection

Body Flap EMA Seal

Rigid Telescope Concept

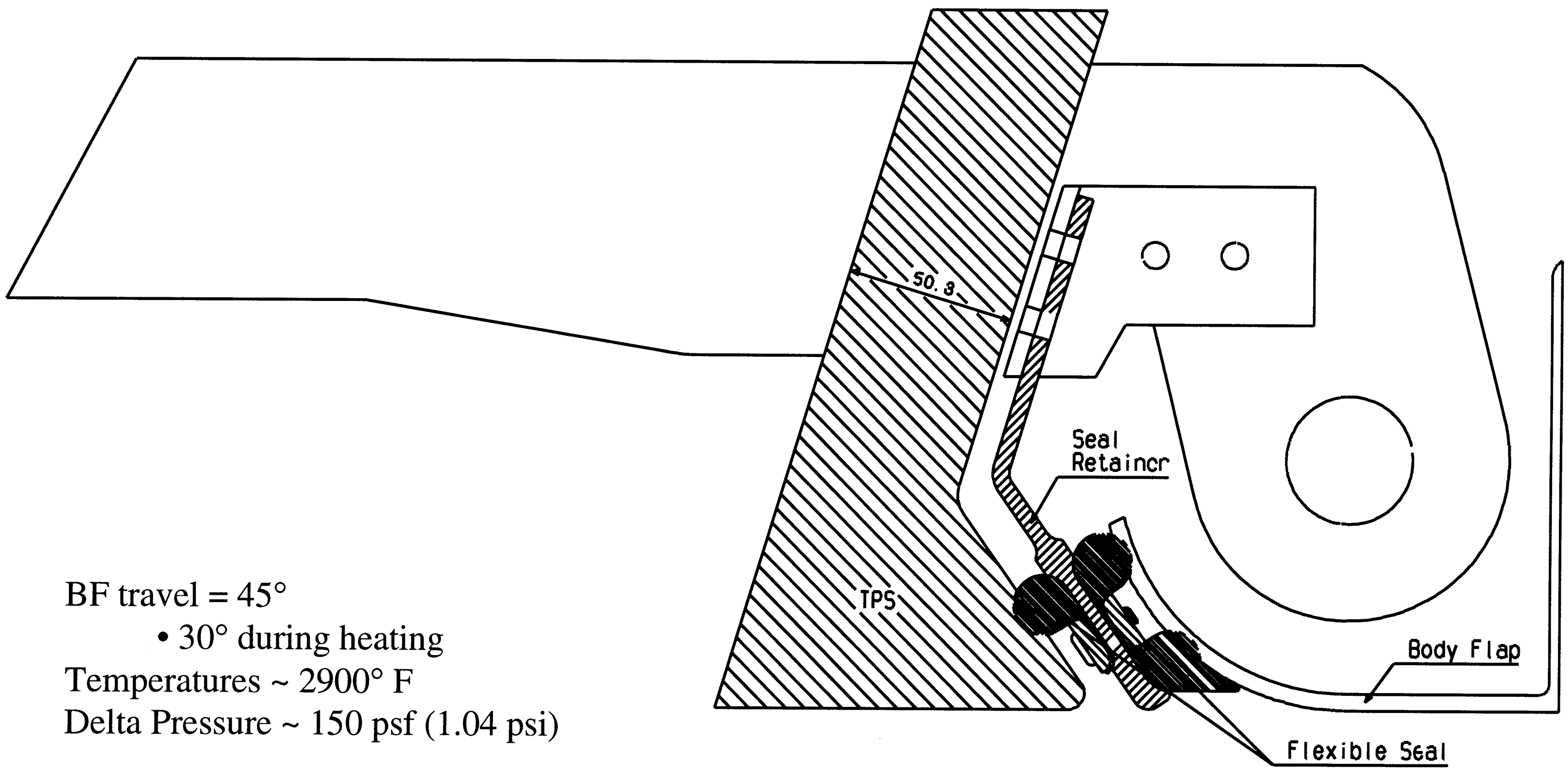


0° Deflection



45° Deflection

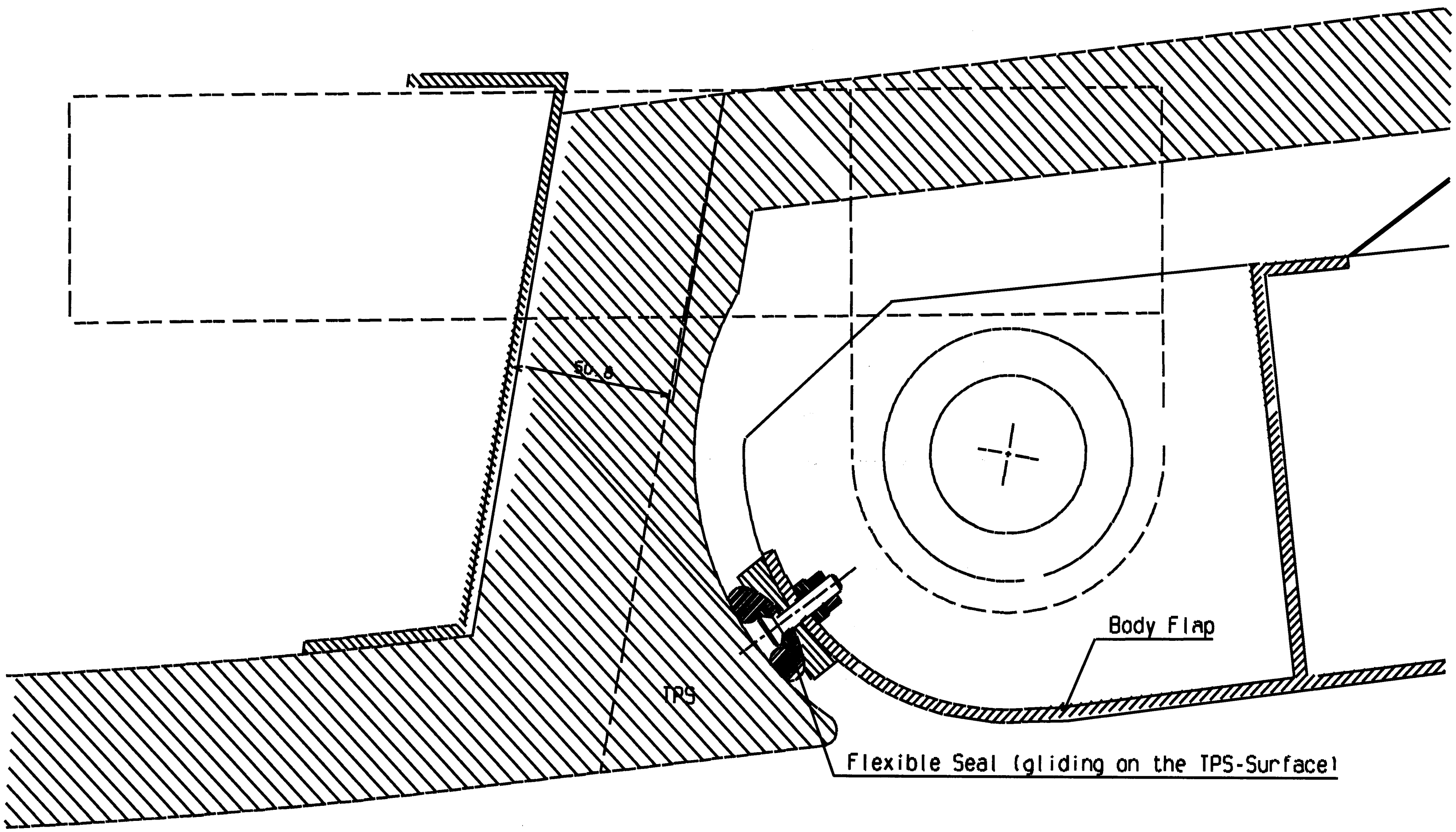
Body Flap Hingeline Seal Concept #1



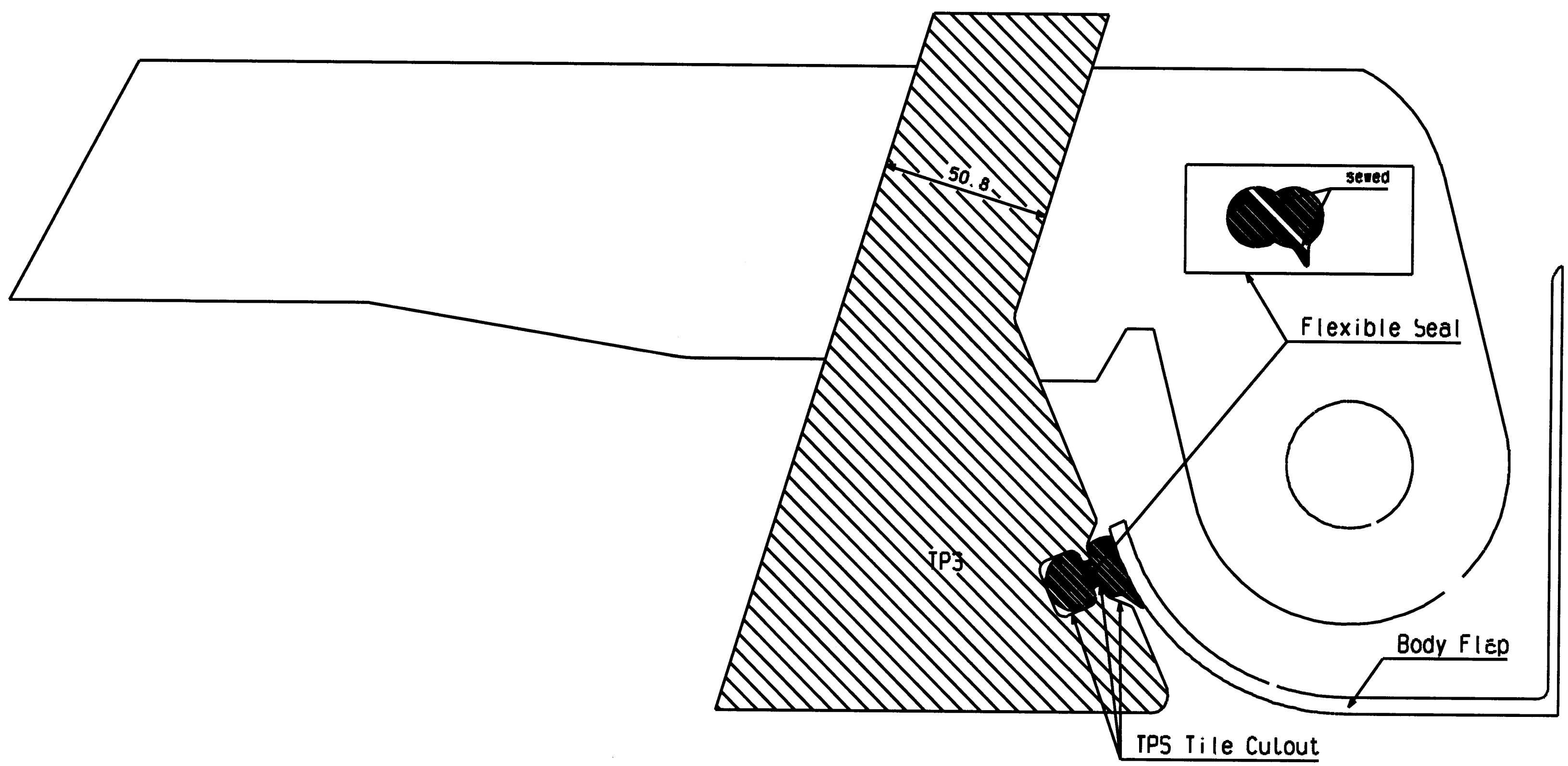
BF travel = 45°
- 30° during heating

Temperatures ~ 2900° F
Delta Pressure ~ 150 psf (1.04 psi)

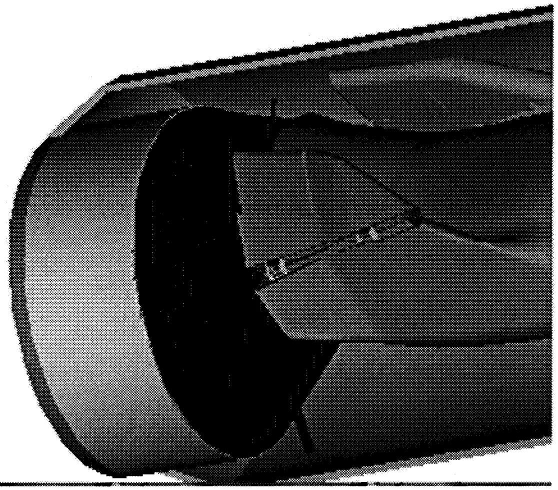
Body Flap Hingeline Seal Concept #2

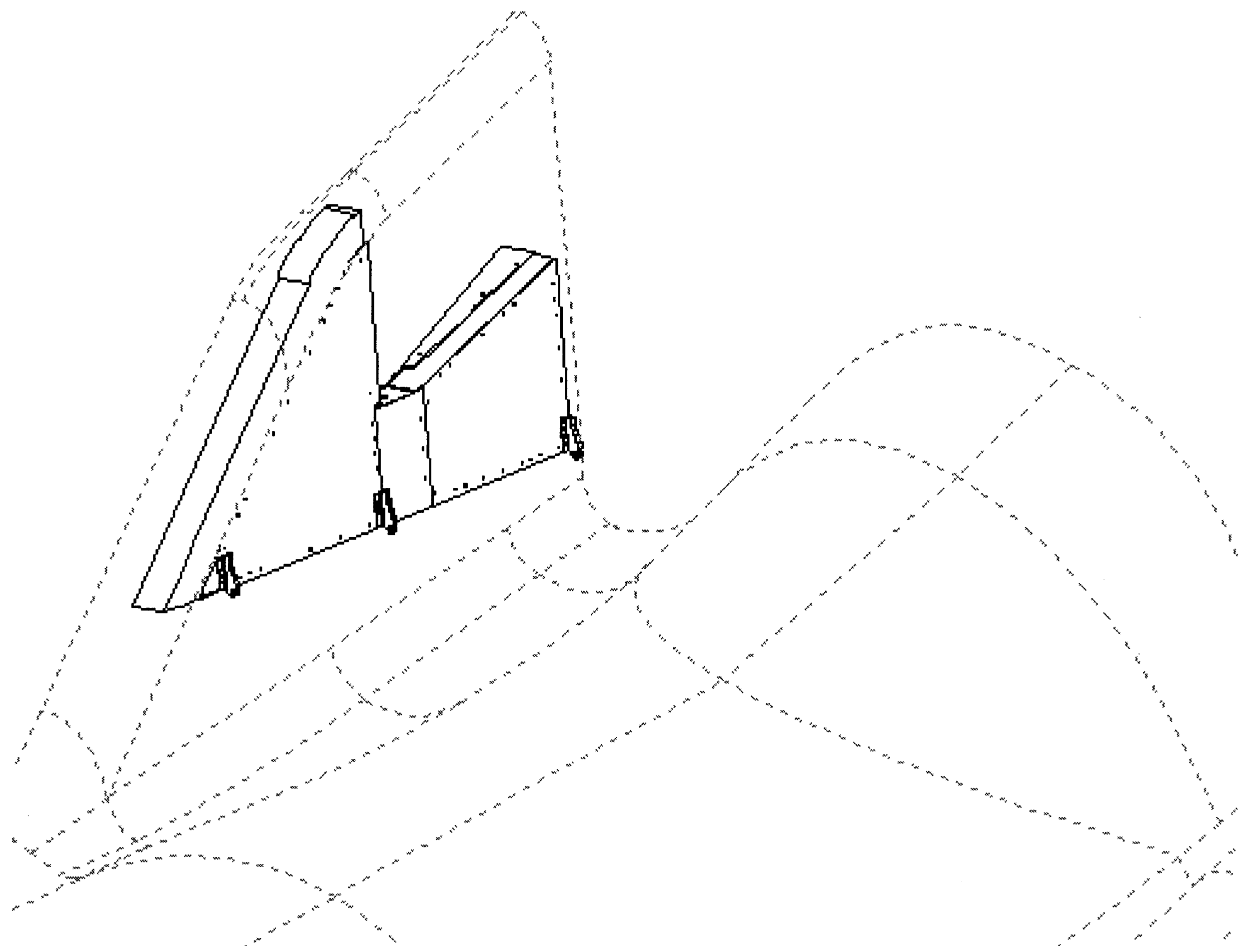


Body Flap Hingeline Seal Concept #3

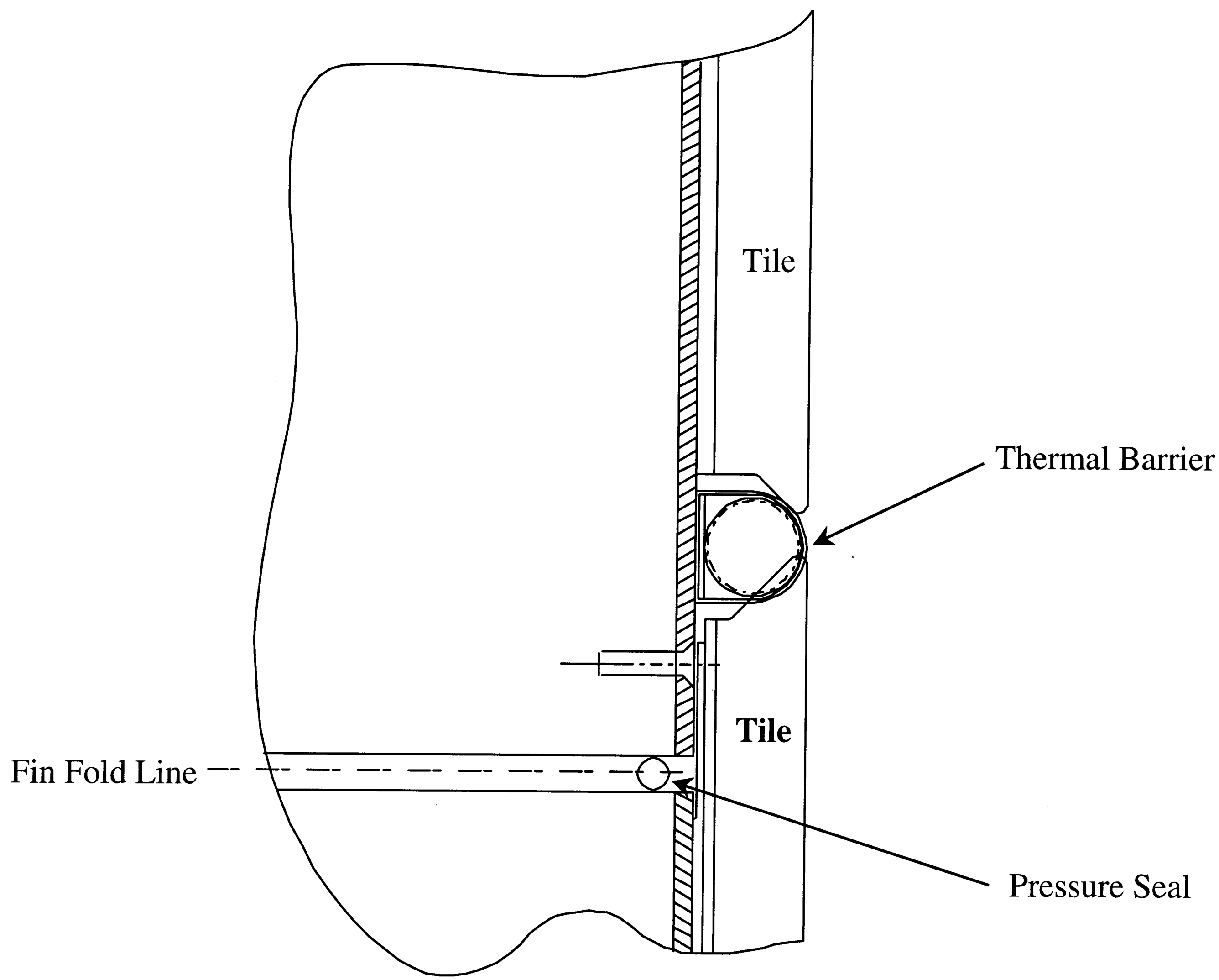


Folding Fin





Fin Fold line Seal



Rudders

Hot metallic structure rudders

- Provided by Fokker Space
- High temperature nickel and iron based alloys
- Skin-stiffener structural system

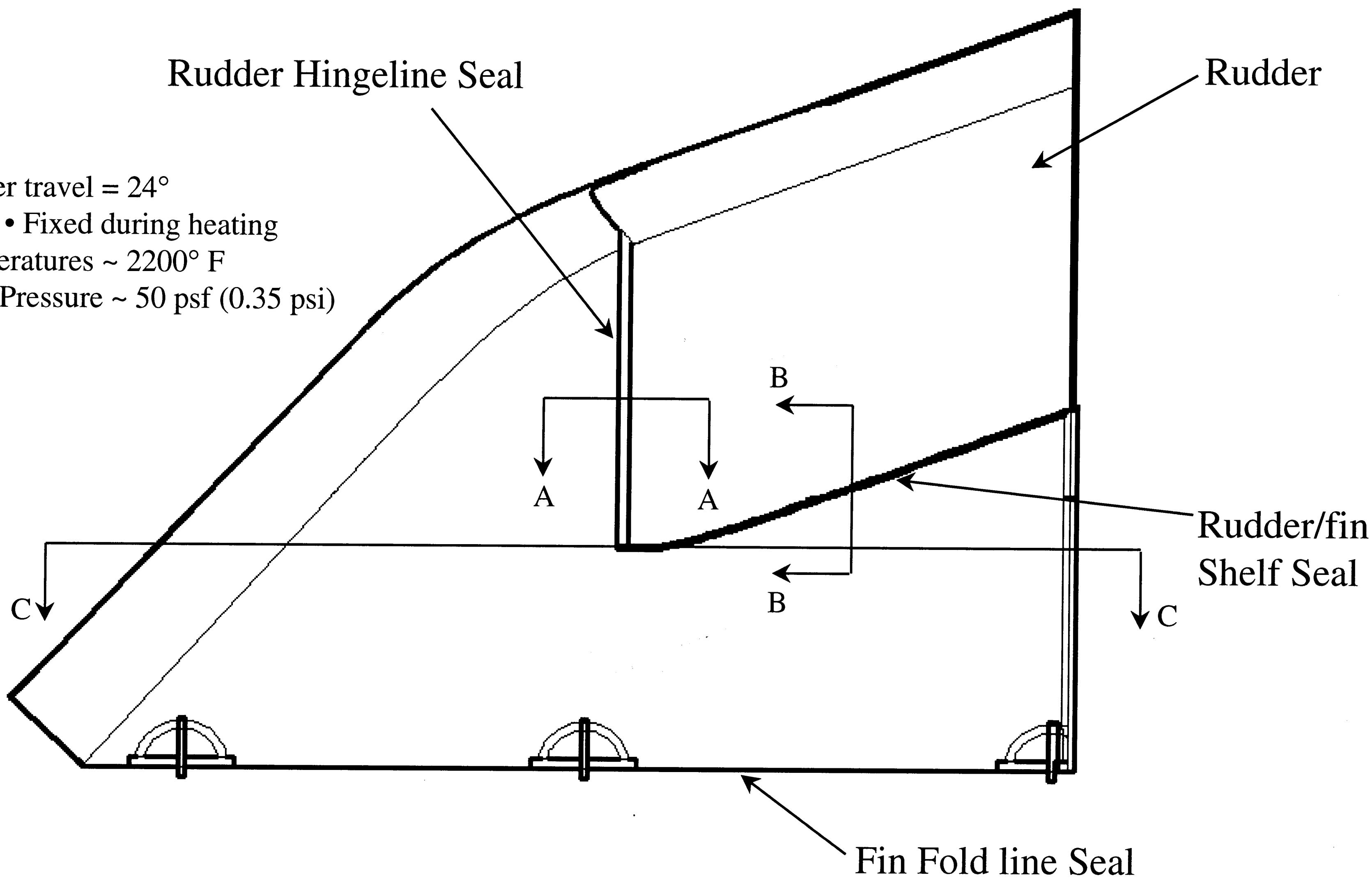
⇒ Hingeline seal

⇒ Rudder/fin shelf seal

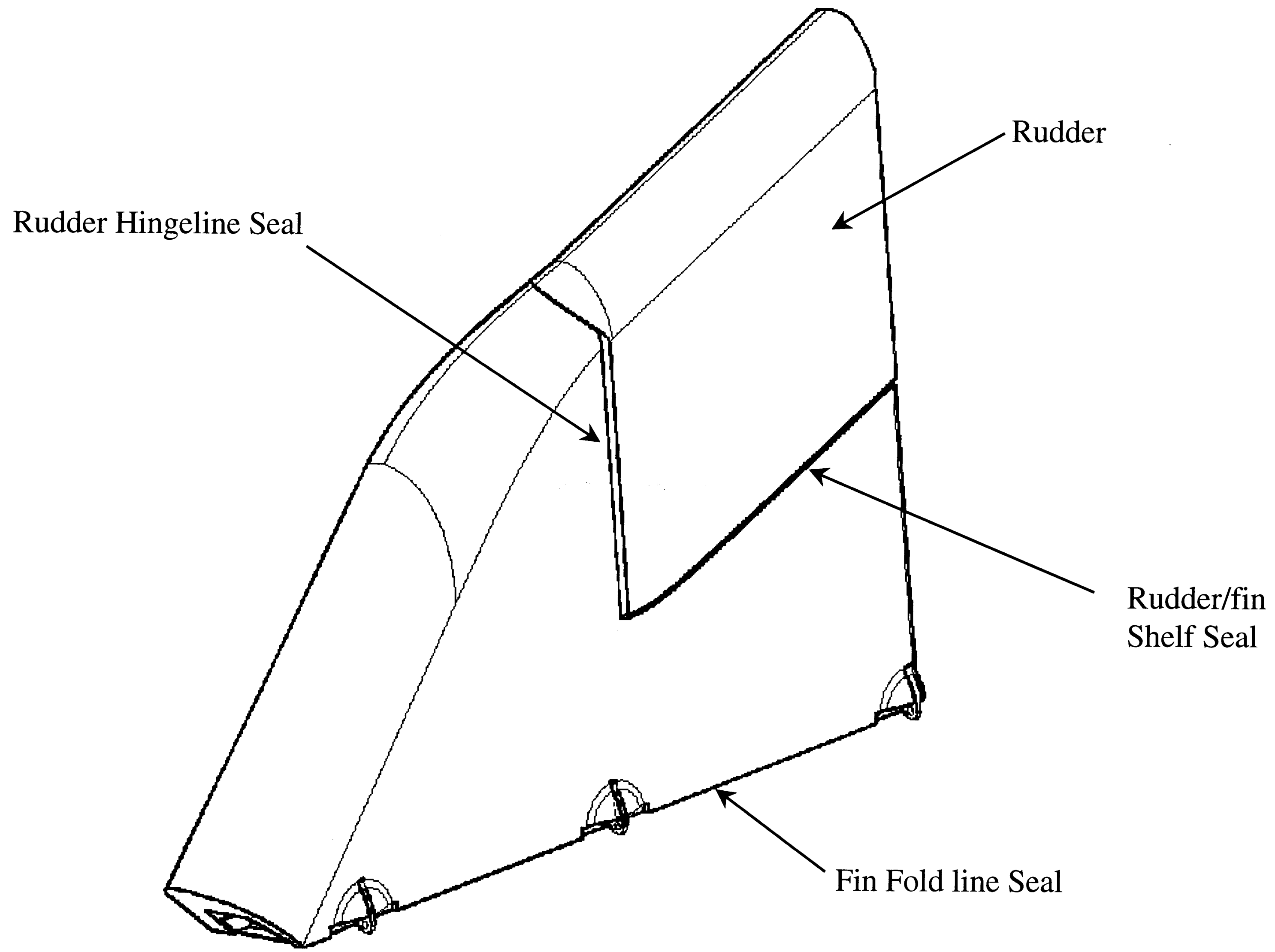
Fin & Rudder Seals

Rudder travel = 24°
- Fixed during heating

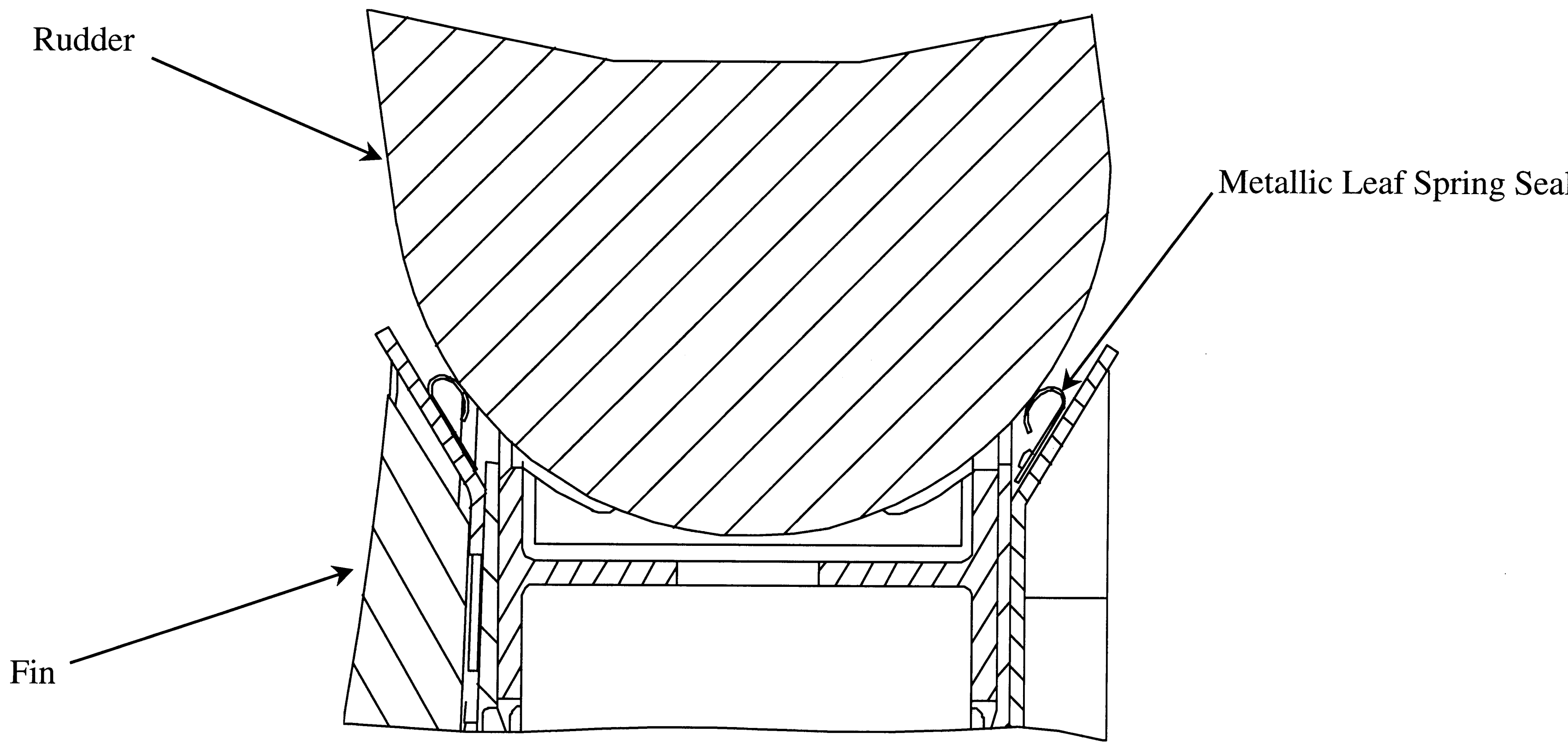
Temperatures ~ 2200° F
Delta Pressure ~ 50 psf (0.35 psi)



Fin & Rudder Seals

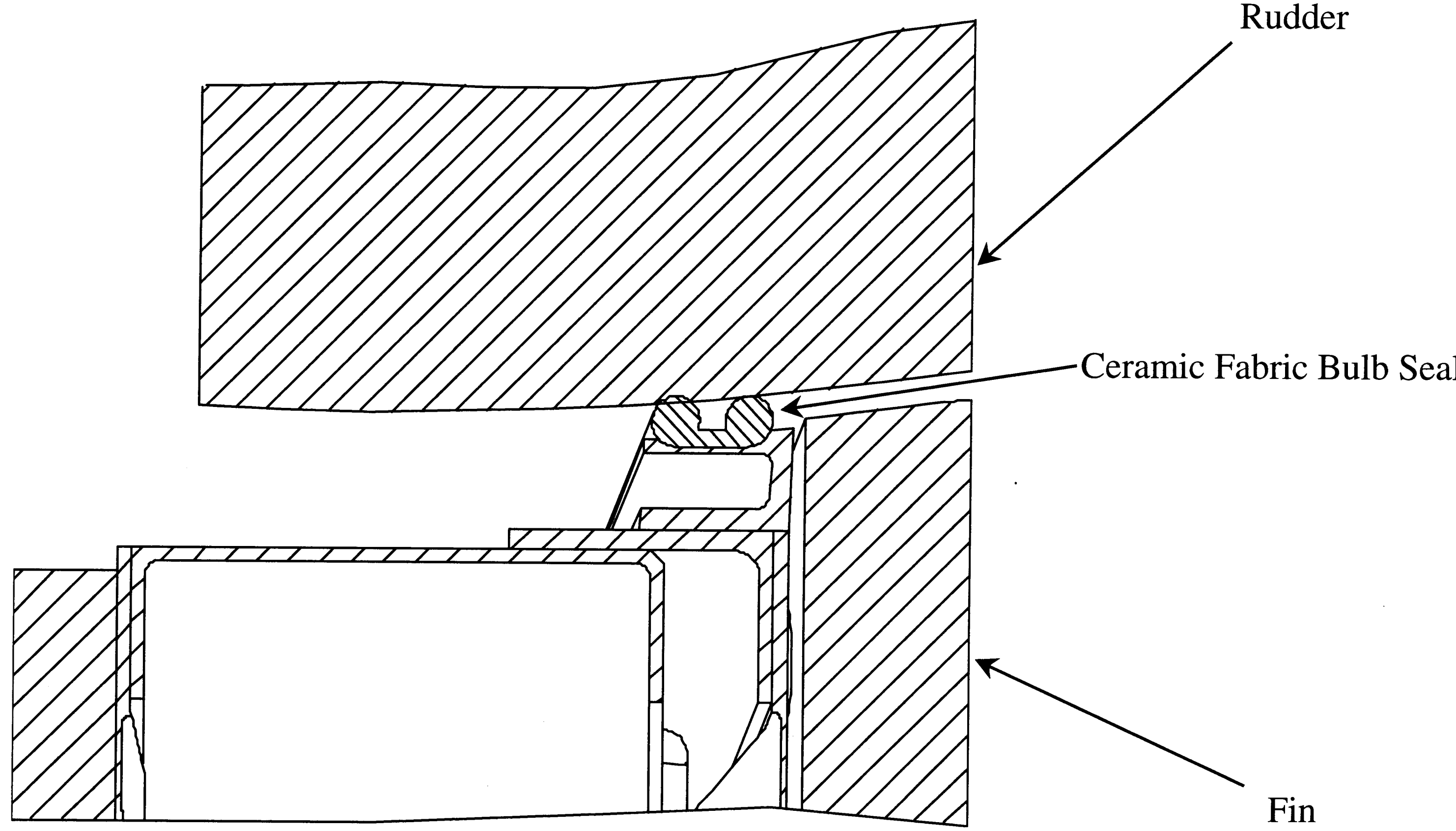


Rudder Hingeline Seal



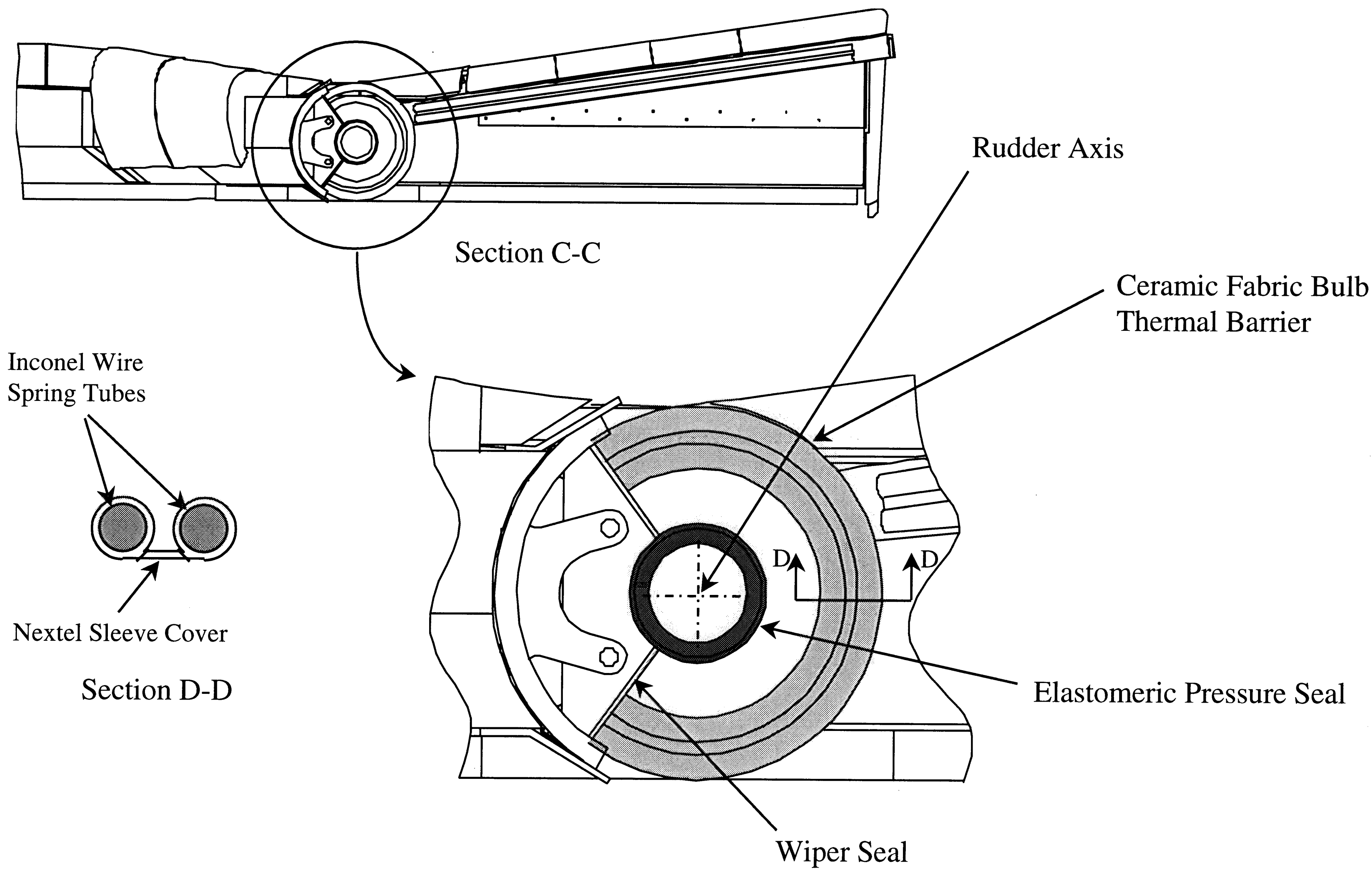
Section A-A
(rot. 90 CCW)

Rudder/fin Shelf Seal



Section B-B

Rudder Base Rotary Seal



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13. ABSTRACT ***(Maximum 200 words)***

The 1998 NASA Seal/Secondary Air System Workshop was divided into three major areas with limited materials presented in Volume II: (1) overviews of the (NASA's high speed research (HSR) and DOE's advanced turbine engine systems (ATS)) gas turbine programs and the general aviation program (GAP) with emphasis on sealing methods and results; (2) sealing concepts and methods and results including experimental facilities and numerical predictions; and (3) reviews of the numerical engine simulation and aerospace vehicles and concepts (Trailblazer, Bantam, and X-38).

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